Incipient slippage detection in tactile feedback system

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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

**INCIPIENT SLIPPAGE DETECTION IN TACTILE
FEEDBACK SYSTEM**

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SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING

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بسم الله الرحمن الرحيم

إن الحمد لله نحمده و نستعينه و نستغفره، و نعوذ بالله من شرور أنفسنا و
من سيئات أعمالنا، من يهده الله فلا مضل له، و من يضلل فلا هادي له، و
أشهد أن لا إله إلا الله وحده لا شريك له و أشهد أن محمدا عبده و رسوله.
أما بعد:

Abstract

The physical isolation of surgeon from surgical instrument and patient inherent to the master-slave setup of the tele-Robotic Minimally Invasive Surgery (RMIS) results in a total loss of sense of touch compromising both diagnostic (e.g. palpation) and assistive (e.g. grasping and suturing) surgical tasks conducted. Grasping and manipulating tissue without access to coherent tactile sensations impedes natural grasping with one being unable to directly gauge excessive and inadequate grasping forces leading to higher rates of tissue perforations as well as slippages. To date, the tactile feedback system consisting collectively of i) tactile sensor to measure conditions on contact interface, ii) tactile display to relay tactile sensation to operator and iii) integrating control to relate sensor output to the tactile display, represents the foremost approach for restoring necessary tactile feedback. In contrast to systems already established for palpation and shape, there exists a dearth of systems for facilitating grasping mainly due to the complexity of innate human grasping response. The current work investigates the necessary formulation and configuration of such a tactile feedback system and its subsequent application to resolve impaired grasping in RMIS.

A three-step approach was undertaken to resolve the problem of impaired grasping in RMIS through tactile feedback system. The first step involved the review of literature pertaining to psychophysical studies of precision human grasping to identify and understand the intrinsic biology and derive the physiological requirements. The next step involved the identification and selection of potential hardware and approach analogues to human physiology for both sensing and display elements of the tactile feedback system together with a framework for effective application of the entire system. The final step consisted of modeling and experiments conducted necessary for the effectiveness of the framework.

The solution developed within the thesis is aimed to provide for sufficient grasping transparency within a teleoperation setting. It consists of a novel incipient slippage tactile feedback system designed to be implemented under a unique framework with an underlying hybrid shared control architecture to compensate for intrinsic delay in data transmission between local and remote sites. The framework proposed is designed to facilitate prompt partial to fully automated response on the remote site to mitigate communication lag in the event of imminent slip while relaying incipient slip sensation to the master allowing for operator awareness. The critical element for the proposed system is quick detection of incipient slippage. The results obtained from experiments conducted with the designed piezoresistive incipient slip sensor achieved a 77% detection rate with a best detection time of 0.2s prior to incipient slippage. Failed detections were observed in situations when normal force applied were close to the minimum and maximum operational limits of the sensor. To facilitate the framework, an extension to Ho's Two Dimensional Beam Bundle was formulated to enable analysis of microvibration phenomenon at the moment of incipient slip model. By modeling each individual beam's vibration with a spring and dashpot configuration, the characteristic frequency and threshold magnitude unique to incipient slippage could be identified. As accurate identification of stiffness and damping ratio values remains a source of potential error, further study and elaboration on the methodology for identifying these parameters would be required.

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Chapter 1

Introduction

Minimally Invasive Surgery (MIS) procedures, such as laparoscopic cholecystectomy or prostatectomy, represents a considerable shift from conventional surgical paradigm by targeting the minimization of trauma inflicted upon a patient to achieve reduction in pain, intra-operative blood loss and recovery time. The ensuing increase in level of surgical difficulty due to limited direct visibility and surgical access had paved the way for teleRobotic Minimally Invasive Surgery (RMIS) which entails remote manipulation of the surgical implements via slave robot arms through a master console. Though effective through its incorporation of features such as tremor reduction and increased range of motion gained coupled with finer, more precise motion control, the physical isolation of surgeon from surgical instrument inherent to the master-slave setup of RMIS has resulted in the total loss of sense of touch¹, an intrinsic element for fine dexterous manipulation in humans [1]. In that respect, the loss of tactile sensation in particular represents a serious concern for current RMIS procedures due to the limitations such a loss imposes upon the surgeon when performing both diagnostic and assistive surgical tasks such as palpation [2], suturing [3] and grasping of tissue [4].

1.1 Background

MIS describes a radical approach to surgery that in primarily seeking to minimize the degree of trauma inflicted upon a patient, inadvertently degrades a surgeon's sense of awareness pertaining to touch and vision. The benefits in minimizing trauma during surgery derives from the promise of reduced risk of complications arising from infection and scar adhesion [5], alleviation of the level of pain and intra-operative blood loss experienced [6], as well as a shorter recovery time coupled with improved cosmetics [7]. In keeping with that said objective however, effecting required surgical tasks within MIS would necessitate foregoing the conventional large entry wounds relying instead on small keyhole incisions coupled with the use of specialized slender and rigid instruments to access the

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¹ Sense of touch is representative of haptics perception, a combination of kinesthetic (sensation of the internal state of the limbs such as weight) and tactile senses (sensation arising from contact on the skin), both key elements in human perception and manipulation.

operating site within the body. This *indirect* approach to surgery consequently culminates in the following drawbacks: i) limited dexterity due to restricted instrument motion, ii) skewed hand-eye coordination and limited depth perception arising from dependence on 2D monitors/laparoscope, and iii) a lower level of comfort and familiarity for the surgeon resulting from poor ergonomic design of the surgical instrumentation and working space [7]. In addition to the aforesaid limitations, the intervention of surgical instrument resulting in the absence of direct contact between skin and the targeted tissue within the body reduces the degree of kinesthetic feedback accessible to the surgeon as well as eliminates tactile feedback. Overall, these combined shortcomings associated with the MIS setup compromises the degree of control as well as feedback afforded to the surgeon compelling greater demands upon the surgeon's level of skill and concentration in contrast to conventional open surgery.

In alleviating the demands placed upon an MIS operating surgeon, the inception of RMIS has helped redress a number of the aforementioned deficiencies primarily through the latter's imbued high precision and accuracy. Fundamentally a telerobotic system, RMIS typically features a master console from which the surgeon could remotely control one or more robotic slave arms, each effecting the movements of individually interchangeable surgical instruments with great precision while a dedicated dual lens laparoscopic camera connected to a stereoscopic vision system provides for visual feedback. Features of RMIS include: i) stereoscopic vision system to restore the missing depth perception, ii) incorporation of tremor reduction through low-pass filters coupled with scalability of movements within the robotic control system (together with the improved vision) to remedy issues associated with the skewed hand-eye coordination, iii) wrist-like end-effector design that provides up to 7 degrees of freedom [8] (e.g. the Endowrist low-friction cable and pulley design) for increased range of motion and dexterity, as well as iv) integration of ergonomic design factors as evident in the replicating of hand, instrument and eye placements as if within a conventional open surgery to help reduce surgeon's fatigue and unfamiliarity. However, dispelling with direct manual control of surgical instruments mechanically isolates the surgeon's hands from the operating site effectively cutting off any direct means of force transmission

and resulting in the total elimination of *both* kinesthetic feedback and tactile sensation as shown in Figure 1.1.

Figure 1.1 Increasing degradation of sense of touch from open surgery to RMIS

This degradation or complete elimination of both kinesthetic and tactile feedbacks endemic within both MIS and RMIS has resulted in a number of identifiable problems which have been extensively studied upon within literature. In her review on the state of haptics replication for RMIS, Okamura [1] had questioned the repeatability of force application when conducting suturing tasks within the RMIS setting without access to haptics perception. Highlighting the time lag factor, Garcia-Ruiz et al. [9] had deduced that the resulting mismatch between the remote control and instrument response due to the missing tactile sensation in RMIS leads to increased surgical times. Expounding upon the mental state of the operating surgeon, Xin et al. [6] had stated that limitations to both visual and haptics perception as experienced within MIS result in increased cognitive and physical stress leading to reduced accuracy in judgements and estimations. A common approach of these studies had been to directly characterize and quantify the effects missing haptics would have on the performance of individual surgical tasks through comparisons and standard metrics. The effects of missing haptics on three surgical

tasks: i) palpation, ii) suturing, iii) grasping, blunt tissue dissection and other manipulations will be described in the following subsections:

Palpation

Palpation involves the probing of tissue by hand, typically within a pressure range of 10-40 kPa [10], to ascertain both tissue characteristics and conditions for the safe assessment of intra-operative findings as well as the identification of anatomical and pathological structures. While evaluating comparisons between absolute sensory thresholds during palpations within MIS and conventional surgery, den Boer et al. [11] reported an 8.7 times decrease in sensitivity when using a standard 5-mm reusable laparoscopic dissector and a 16 times decrease in sensitivity for the 10-mm variant as compared to barehanded palpation where full haptics perception was accessible. Correspondingly, Way et al [12] had identified missing haptics perception leading on to tissue misrepresentation as a possible factor in 61% of 252 bile duct injuries incurred during a study involving actual laparoscopic cholecystectomies. On the effectiveness of restoring kinesthetic feedback for palpation with RMIS, Tavakoli et al. [13] had reported faster completion times for the localization of a lump embedded within a soft tissue while Mahvash et al. [14] had reported superior results pertaining to the number of palpation task errors committed using a heart model when compared to without haptics or with tactile substitution. However, in her review of haptics feedback for robot-assisted MIS Okamura [1] had asserted the criticality of tactile feedback in palpation due to the reliance on skin deformation for detecting and locating of subsurface lumps during palpation [15].

Suturing

In describing the task of suturing, Okamura [16] had stressed the need for sense of touch especially during the puncturing of tissue with the fine needle, pulling of the suture and tying or tightening of the knot. Kitagawa et al. [17] had further explained that its significance during knot tying is in the prevention of suture breakages as well as damage to the tissue. In connection to this, Bethea et al. [3] had recorded differing mean suture tensions during knot-ties ranging from a minimum of 0.36N for 7-0² Prolene to a maximum of 2.4N for 2-0 Ti-Cron for ideal hand ties as

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² Suture size designations with higher 1st numbers (i.e. 7-0 vs 2-0) having smaller diameters.

compared to 0.29N for 7-0 Prolene to 5.16N for 2-0 Ti-Cron for RMIS without haptics feedback. Adding to that, both Çavuşoğlu et al. [18] and Ruurda et al. [19] had independently reported higher incidents of suture damages/ruptures involving RMIS system without haptics feedback when compared to conventional laparoscopy (which affords a compromised kinesthetic feedback as stated in the prior section) regardless of suture sizes. Pertaining to suturing times, Garcia-Ruiz et al. [9] had reported significantly longer times for RMIS with larger suture sizes 2-0 (605s vs 154s) and 4-0 (462s vs 191s) as compared to conventional MIS. In contrast, restoration of haptics feedback through sensory substitution (i.e. visual representation/alert), as reported in Bethea et al. [4], had allowed for more consistent and exact suture tensions (s.d. ranging from $\pm 0.11\text{N}$ - $\pm 0.83\text{N}$ vs $\pm 0.14\text{N}$ - $\pm 2.46\text{N}$) without any breakages. Schirmbeck et al. [20] reported reduced applied forces (1.32N vs 1.02N) with increasing force feedback during surgical knot tying with RMIS. In the end, Kitagawa et al. [17] had postulated that although force feedback improves accuracy and average force exertion to a certain extent, tactile information would still be needed to maintain the degree of accuracy and repeatability for suturing forces.

Grasping, Blunt Tissue Dissection³ and Manipulations

The assistive tasks of grasping/manipulating and blunt dissection of tissue all involve applying forces upon the surface of the tissue and achieving traction, either through gloved hands or an instrument such as a grasper or forceps. Blunt dissection in particular describes separating of tissues directly with either blunt implements or fingers in order for the surgeon to have a greater degree of control and a more visceral feel of the incision. Pertaining to the effects of compromised haptics, Joice et al. [21] had reported from observing 20 separate laparoscopic cholecystectomies that the most frequent errors were committed while using the grasper, with the errors being predominantly related to either dropping of or causing trauma to the grasped tissue. In a later study on the effectiveness of grasping in MIS, Heijnsdijk et al.'s [22] observation of video recordings involving 10 laparoscopic colectomies and 15 cholecystectomies revealed that only 62% of all grasping actions conducted by the operating surgeons could be considered as successful without any slips, need

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³ An assistive task closely related to grasping which combines pinch and pull actions with a grasper to dissect tissue.

for repeated actions or resulting damage to the grasped tissue. Focusing solely on the trauma caused by graspers, Marucci et al. [23] had surmised that incidences of gall bladder perforations were 13-40% higher in laparoscopic cholecystectomy than in open cholecystectomy. In all three of the aforementioned studies, it is particularly telling that the missing tactile feedback has been cited as one of the main contributing factor to the errors involving slips and trauma during grasping and manipulation of tissue, a fact corroborated by multiple studies (e.g. [24, 25 & 26]). Consequently, efforts to restore haptics have reported relatively positive results with regards to grasping and other dexterous manipulation within MIS and RMIS. Wagner et al. in [27] had reported a minimum reduction of 50% grip force during simulated blunt dissection of an artery with kinesthetic feedback artificially restored. King et al. [28] also observed a reduction in grip force when transferring object within the RMIS setup with their attempt to restore tactile feedback. Collectively however, the number of researches looking into restoring the sense of touch for optimal grasping and manipulation has been few when compared with those focused on restoring for palpation as will be shown in the following chapter.

With regards to the abovementioned paucity pertaining to tactile feedback restoration for grasping and manipulation tasks, a review of the current state of haptics within minimally invasive surgery conducted by Westebring et al. [4] which focused exclusively on the grasping/manipulation task within MIS and RMIS, had failed to report *any* viable system with restored tactile feedback for grasping force and slip sensation. Schostek et al.'s [29] review on the aspects of artificial tactile feedback in laparoscopic surgery was even more explicit when it confined the defined objective of an artificial tactile feedback system solely as “to restore part of the information about *tactile tissue properties*... which would be useful for the surgeon to *better assess intra-operative findings*” with no mention of grasping or manipulation. Therefore in this report, it is suggested that the restoration of the necessary tactile sensations to overcome the limitations imposed upon the assistive task of grasping/manipulation within RMIS merits further investigation and could potentially contribute towards the reduction of failed grasps encountered thereby enhancing the overall safety of current RMIS procedures.

1.2 The Limitations Imposed upon the Task of Grasping/Manipulation within MIS and RMIS

The task of grasping and manipulation of tissue entails maintaining a grip force normal to the contacted surface within a safe region defined as between the minimum force to prevent slip and the maximum force to avoid damaging the tissue⁴ [30]. Within the context of MIS, the typical gripping force range of between 10 N to 20 N [31] and a minimum operating pull force (tangential to the contacted surface) of 5 N [26] while localized pressures ranging from 210 kPa to as high as 650 kPa have been recorded at the tip of the utilized instruments [25]. In stark contrast to grasping & manipulation of tissue within a conventional open surgery setting which affords a close to direct tissue contact through gloved hands under direct vision, effecting surgical tasks within the confines of MIS and RMIS involves the ingression of slender (5-10 mm in diameter [32]) and rigidly elongated (effective shaft length of 300-400 mm [32]) surgical instruments into the body by way of small, strategically-located surgical access points via a trocar⁵ with only the laparoscopic camera providing for visual feedback. Consequently, the task of grasping within MIS and RMIS places greater constraints upon the operating surgeon with him having to indirectly perceive and deliver optimal gripping and pulling forces taking place within the body at the instrument-tissue interface.

The constrained use of the specialized elongated instruments in MIS and RMIS as described above severely impacts the surgeon's ability to conduct grasping tasks in contrast to conventional open surgery stemming from the two-way degradation in actual force transmission from hand to instrument clamp surface. Firstly, translational frictional forces ranging from 0.25 N to that exceeding 3N are generated between instrument shaft and trocar wall during axial motion [33 & 34] while a frictional torque of up to 0.7 Nm [34] arises when pivoting the instrument against the stiffness of the abdominal wall. Next, degradation of force transmission between instrument-tissue contact and surgeon's hand is incurred due to the scaling

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⁴ In blunt tissue dissection, this fundamental task remains but with the need to contend with varying pull force (necessary for dissection) resulting in changes to the minimum and maximum grip forces defining the safe region [30].

⁵ A device functioning as an interface between the patient and outside environment for ingression of instrument that helps to seal insufflation gas and prevent skin rupture.

of forces caused by the fulcrum effect⁶ (ratio between force exerted at hand grip to force generated at instrument tissue contact range from 0.2 to a maximum of 4.5 [36]) as well as the friction inherent within individual instruments (e.g. at joints, where moving parts interface) [34]. In conventional MIS, these extraneous forces coupled with the degradation of force transmission directly confounds kinesthetic feedback while the interceding instrument between contact interface and glabrous skin eliminates tactile feedback completely to the detriment of the surgeon's capacity to perceive contact forces and control the necessary forces to be applied externally. The effects on a surgeon's ability to grasp and manipulate tissue are accordingly more severe in the case of RMIS where *both* tactile and kinesthetic feedbacks are completely eliminated due to the physical isolation of the master-slave setup. However, it is the absence of tactile feedback inherent to both MIS as well as RMIS which represents a severe deficiency to the surgeon's ability to grasp or manipulate an object due to his reliance upon the latter for maintenance of optimal grip force as will be shown in the following section.

1.3 The Need for Tactile Feedback to Maintain Optimal Grip Force

In maintaining optimal grip force while conducting tasks such as grasping and blunt tissue dissection, failure to access tactile feedback constitutes a more critical deficiency for the surgeon due to the innate reliance of tactile feedback for dexterous manipulation. To that effect, Johansson & Westling [37] had earlier reported the vigorous responses of Fast Adapting Type I, II (FAI & FAII) and Slow Adapting Type I (SAI)⁷ tactile afferents to skin vibrations signifying imminent slipping for the adaptation of grip force to successively different friction surfaces of *passive* objects when lifted with precision grip. The more recent study on the grasping of *active* objects conducted by Macefield et al. [38] had again recorded consistent FAI⁸ tactile afferent signals, this time in response to the introduction of external load forces (tangential to contacted surface) prior to the triggering of the compensating increased grip force response. On the flip-side, eliminating tactile

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⁶ A result of surgical instrument placement in MIS/RMIS where the abdominal wall on which the instrument sits on effectively acts as a pivot point during instrument manipulation [35].

⁷ SAs respond to prolonged and sustained stimulus while FAs only respond to rates of stimulation. Type Is have small, well-defined sensory boundaries while Type IIs' are large and ill-defined.

⁸ Meissner's corpuscles attached to FAI tactile afferents have a high density of 140/cm² on the glabrous skin of the fingertip, a small receptive field (area of detectable stimulus) size of 13mm² and are located 0.7 – 1mm just below the epidermis layer within the dermal papillae.

afferent response through anesthetic block of the digital nerves was found to have resulted in both an increased latency as well as a reduction in magnitude of each of the grip force response to both external load forces [39] and diminished friction [40]. In short, the studies mentioned above have all emphasized on the singular role of tactile afferents and tactile feedback during grasping for adapting of grip forces to either reduction of friction or increase in external load forces for the maintenance of optimal grip force, as corroborated in other similar studies [41, 42 & 43].

Drawing corollaries from the aforementioned psychophysical studies, it could therefore be established that: i) the two tasks of adapting grip forces to different surface coefficients of friction and reacting to unexpected load forces constitute critical features for the maintenance of optimal grip force during precision grip and ii) that grip force response for both rely exclusively on the tactile afferent signals with a strong predisposition towards responses from FAIs. The following sub-sections elaborate further the adaption of grip forces for the two abovementioned tasks:

I. Adaption to different levels of friction

Adaption of grip forces to different levels of friction constitutes a two-tiered response [37, 40 & 43] as manifested in the lifting of a passive object weighing 400g in [37]. The first tier *initial adjustment* to the friction would have occurred within the first 0.1-0.2 s of contact [37] of the preload⁹ and early loading¹⁰ phases involving increase of grip force to load force ratio to overcome the surface slip ratio¹¹. This increase triggered by non-visible slips is achieved after circa 74 ms through a short period of decreasing load force possibly coupled with an increased grip force [37 & 43]. Insufficient upgrade to the ratio during this initial adjustment would lead to the second tier *secondary adjustment* involving an increased grip force rate during the later loading and possibly static¹² phases [40]. Both periods' unique increases were similarly triggered through non-visible slips occurring after circa 74 ms [37] from that initial trigger. In each of the responses during the initial

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⁹ Period from initial contact up to when load force begins, characterized by increasing grip force.

¹⁰ Period from start of increase in load force up to when object leaves support characterized by increasing grip and load force in tandem.

¹¹ The specific ratio of grip to load forces below which lifted object starts to slip that is dependent on the coefficient of friction at the contact interface.

¹² Period of time starting from when lifted object has stopped at desired point of elevation and characterized by approximately constant ratio of grip to load forces.

and secondary adjustments, an increased firing rate from the FAI tactile afferents was recorded after a minimum delay of about 10 ms due to either full or localized slips [37].

II. Reaction to unexpected load forces

Unexpected load forces refer to external forces other than weight that arise when gripping an active object capable of independent motion [39, 44 & 45]. Gripping response to such unexpected load forces consists of an initial *catch-up response* and a *tracking response* for load forces increasing for an extended time length [44 & 45]. The catch-up response appear early during the initial loading phase of load force featuring a parabolic grip force rate response within a fixed duration (0.2-0.25s) with the peak grip force rate scaled proportionally to the load force rate which leads to the final grip force being linearly proportional to the finalized load force [44]. Johansson et al. [45] had observed that the latency period between onset of load force and initiation of grip force response decreases as the load force rate increases, with a minimum latency of 82ms once a threshold load force of 0.19N was reached which corresponds to the critical grip to load force ratio whereupon *localized* slips take place. Similarly, the rate of grip force response during the tracking response for extended loading phase duration is scaled directly to the load force rate thus maintaining a constant grip to load force ratio [44] to prevent slip. Pertaining to afferent response, Macefield et al [38] had observed that the response of FAI tactile afferents reflected both the duration (matching the onset and cessation of loading force) and the rate of load force increase, with almost half of all FAI afferents measured responding by 8 ms¹³ minimum.

Thus with reference to maintenance of optimal grip forces, the ability to adapt to different fictional surfaces as well as react to unexpected load forces enable quick and efficient scaling of the grip force response and require tactile afferent signals, particularly FAIs', responding to non-visible slip events. Specifically, accurate and timely scaling of grip force response could be achieved and implemented after a lapse of just 74 ms and a minimum of 84 ms from non-visible slip events for adaption to different frictional surfaces and reaction to load forces respectively. Consequently, it could be surmised that slip detection during grasp through tactile

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¹³ This was achieved with the highest load force rate of 32N/s.

afferent signals constitutes a common intrinsic means for the automatic gauging of load forces/ friction and thus for the timely engaging of grip force response.

1.3.1 Slip Detection during Grasp

There are two variants of detectable slips which could occur during grasping namely the overall and the localized slips. The first overall slips signify a mass slipping of the grasped object's surface occurring most frequently during loading and static phases of lifts when ratio of grip to load forces dip below the slip ratio. Though invisible to the naked eye, the resulting vibration of the glabrous skin detectable through accelerometers elicit responses from *all* tactile afferents (i.e. FAI, FAII, SAI and SAII) following which automatic grip force response occurs [37]. On the other hand, occurrences of the second localized slip are limited to within small segments of the skin in contact with the grasped object, occurring *close to* or *during* periods of declining grip to load force ratio. These limited movements do not suffice to induce any detectable vibration and result in responses from only the FAI and SAI tactile afferents that could still elicit weak upgrades in grip force. An important observation of local slips, as stated by Johansson & Westling [37], is that they are characteristic of the period of time leading up to the overall slip within the static phase of lift. The timing of localized slip prior to overall slip thus alludes to its function as a prelude to actual slip occurrences.

Figure 1.2 A. Visualization of stick and slip region on contact surface. B. Growth of slip region with advancing contacted plate (adapted from Tada et al. [46])

To that effect, localized slip events are the direct results of uneven distribution of forces on the contacting skin-surface interface generated during grasping. In [43], Johansson & Westling stated that the elastic properties and innate curvature of the skin around the grasping fingertip result in the contacted glabrous skin having a high normal pressure in the centre surrounded by a low normal pressure termed the stick and slip regions respectively as shown in Figure 1.2A. When either unexpected load force is exerted or in the event of failure to adapt to low friction, the lower normal forces within the slip region result in a lower opposing frictional force inducing multiple localized slips within this region and fostering an expansion of the slip region as seen in Figure 1.2B. The *growth* of the slip region elicits responses from increasing numbers of FAI and SAI tactile afferents whose receptive fields are located within the expanding slip region thus providing the necessary impetus to induce an increase in grip force [37]. Further growth of the slip region to about $\frac{3}{4}$ of the contact area will then result in an overall slip, eliciting FAI, FAII and SAI tactile afferents as described above [37] inducing an even stronger grip response.

The progressive growth of the slip region within the contact area during grasping thus describes a phenomenon which constitutes a critical element of the slip detection feature for maintaining optimal grip force. Taking cues from the study conducted on precision gripped passive objects, Westling & Johansson [40] described the occurrence as consisting of the following two concurrent events: a centrifugal movement of the skin deformation front and a perpendicular skin displacement. In observing the contact area between the glabrous skin of the index finger and surface of object during initial grip for two subjects, they observed an initial rapid radial growth of the contact area estimated at 50 mm/s corresponding with an initial low grip force of below 1N which steeply tapered down to a negligible rate at just over 5N along with a displacement rate repeating the same trend decreasing from a high of 15mm/s to less than 5mm/s in the same period. It is particularly significant that the estimated increase in the number of FAI and SAI receptive fields deformed mirrors the aforementioned growth rate (high initial rate at low grip force followed by a steep decrease, $\frac{2}{3}$ of which consists of FAI) causing them to respond. Consequently, a corollary could be drawn in that the slip event consist of a symmetrical receding of the area of contact together with the stick

region within which the same FAI and SAI tactile afferents respond resulting in a grip response.

1.3.2 Summary of Section

This section describes the titular role of the tactile afferents in maintaining optimal grip force while grasping. It establishes that the ability to adapt to different surfaces as well as react to unexpected load forces are crucial to the maintenance of optimal grip force and that both of these features rely heavily on the FAI tactile afferent signals generated when either local slip occurs as well as when it develops further into overall slip. It further ascertains the slip events as an inward radial growth of the slip region front which elicits the aforementioned tactile afferent response. Consequently, grasping without the ability to access the relevant tactile feedback as experienced by surgeons operating within the RMIS setting may be at the root of the errors involving tissue slippage and trauma listed earlier and thus represents a significant deficiency within the RMIS approach. The underlying research task of this report is therefore presented as the formulation of a tactile feedback system capable of i) detecting actual localized slips occurring on the surface contact and ii) timely replicating the growth and decline of the slip region within the contact area characteristic of the slip event to facilitate optimal grasping when incorporated into the RMIS setting. It is envisaged that it will lay the foundational work needed to build a prototype of the tactile feedback system designed to restore the missing necessary tactile sensations for gripping within RMIS. Such a system could be further utilized as a platform to study incorporation of localized slip detection/sensation replication for effective control within the RMIS setting.

1.4 Incipient Slippage Tactile Feedback System

In addressing this innate deficiency of RMIS, a tactile feedback system is designed with the sole purpose of measuring the distribution of grip and load forces imposed upon the contact surface of the slave instrument (e.g. the entire jaw of a Babcock grasper) during grasping, determining the presence of an imminent slip event and ascertaining the magnitude of grip force and subsequently replicating the appropriate conditions remotely onto the glabrous surface of the operating surgeon's fingertips at the master console in real-time for him to be able to respond.

In other words, it attempts to stimulate the sensations on the surgeon's fingers that would allow him to maintain optimal grip force while conducting the grasping or manipulation task within RMIS. In the course of a single grasping action, a tactile sensor mounted onto the contacting tool surface will detect and transduce the distribution of impinging forces as well as the occurrence of any local slip events into electrical signals before relaying it through a data processing interface to a tactile display in direct contact with the operating surgeon's fingertips at the master console¹⁴. The signals are interpreted for replication of apt tactile sensations which takes place by way of the tactile display through direct deformation of the skin surface, typically through an array of pins or other controlled mechanical implement termed tactor.

Figure 1.3 The tactile sensor, control system and tactile display components of a complete tactile feedback system (adapted from Culjat et al. [47])

The conception of a complete system thus requires implementation of the abovementioned sensing, control and display components (as seen in Figure 1.3), which must take into account the grip force response characteristics described earlier in Section 1.3. The two main forms of tactile feedbacks to be displayed

¹⁴ The tactile sensor could be classified into two mainstays namely those that seek to ascertain *static* perception of object shape and *dynamic* sensing defined as sensing during motion to obtain perception of high spatial and temporal frequencies crucial for fine surface features/textures and dexterous manipulation

consist of a normal force feedback (10-20 N [12]) to reflect grip force and the rate of coverage (maximum radius of 8 mm, maximum radial speed of 50 mm/s, maximum depth of 3 mm, maximum rate of displacement of 15 mm/s [21]) to simulate slip region growth and elicit grip response. Additionally, the tactile feedback system will operate under a unique framework designed to mitigate delay in communication between the remote and local sites. The following section describes first the schematic view of the designed tactile feedback system followed by the proposed framework.

1.4.1 Schematic View of Tactile Feedback System

The tactile sensor would consist of two separate sensors namely the center of pressure (CoP) tactile sensor to measure the magnitude and location of the normal force and a slip sensor to determine evidence of local slip as seen in Figure 1.4. Figure 1.5A shows the schematic view of CoP sensor which is made up of a pressure conductive rubber layer 2 sandwiched between two flexible conductive layers 1. The pairs S1 and S4 as well as S2 and S3 are electrode pairs located on the edges of the top and bottom conductive layers respectively. By applying a constant voltage V_0 , the total current flow between the top and bottom layer corresponds to the magnitude of whole normal force distribution while the center position of the measured current distribution flowing between the two layers corresponds to the center of the normal force distribution [48]. The slip sensor detects an incipient slip through the high frequency voltage change caused by the signature transition between static and kinetic friction when sufficient tangential load is applied. The sensor consists of an electrode pair spiral pattern underneath a layer of pressure conductive rubber as seen in Figure 1.5B. When normal force is applied onto the sensor, the resistance reduces from infinity (when unloaded) resulting in a drop in output voltage V_p . When tangentially loaded to the point of localized slip, a high frequency voltage output V_p measuring as high as several tens of kilohertz resulting from the transition between static and kinetic friction is induced. The high-frequency segment is then extracted by applying a discrete wavelet transform and converted into DWT power used for detection.

Figure 1.4 Schematic view of the Tactile Feedback System

Figure 1.5 A. Schematic view of CoP sensor, B. Schematic view of the slip sensor
(Adapted from Teshigawara et al. [49 & 38] respectively)

Figure 1.6 Conceptualization of the Slip & Force display elements

The tactile display would consist of a closed-loop servomotor-actuated z direction table force display and a slip display which features a pneumatically actuated balloon-based tactor as shown in Figure 1.6. The display thus provides two critical forms of actuation: a monolithic normal grip force as well as the growing/decreasing indented front of the balloon-based tactor for slip. The output voltage obtained from the CoP sensor is read through an A/D convertor and the value is fed into a microprocessor. The microprocessor will then output the necessary value to be fed to the servomotor which will then actuate the table to the appropriate force. For the frequency component, a range of values for the DWT power is defined with which a localized slip event is assumed to be present. This analog value is converted by the A/D convertor and fed into the microprocessor which would then signal the solenoid valve to release the appropriate pressure into the balloon-based tactor for a controlled rate of expansion which would elicit the grip response.

1.4.2 Tactile Feedback System Framework

Figure 1.7 Tactile feedback system framework

Figure 1.7 shows the framework proposed in this work within which the incipient slippage tactile feedback system will be implemented. The task of the framework is to facilitate prompt response at slave/remote site in the event of imminent slip in order to mitigate the intrinsic lag time in remote-local communication while maintaining persistent tactile feedback at local/master site thereby sustaining grasp transparency. This is achieved through the implementation of a hybrid shared control in the form of the controller which utilizes the tactile feedback from the tactile sensor to respond appropriately at the slave (i.e. F_{FC}) in the event of imminent slip as well as provide appropriate tactile feedback to the master by means of the incipient slippage model which will be described in detail in Chapter 5.

1.4.3 Summary of Section

This section provides a description of the overall concept of the incipient slippage tactile feedback system planned for replicating normal grip force as well as localized slip events during grasp consisting of the tactile sensor and display designs integrated within a single framework. The utility of the system is its ability to simulate the characteristic expansion and contraction of the contact area to stimulate the required FAI tactile afferents for effective gripping response during grasping and blunt tissue dissection.

1.5 Objective and Scope

The overall aim of this work is to develop a tactile feedback system-based solution for achieving grasp transparency in RMIS to preserve natural grip response. In order to achieve this aim, the following objectives were identified:

- **To characterize and ascertain the necessary parameters and events required during grasping of object.** Literature review pertaining to psychophysical studies conducted on active and passive manipulation of object was undertaken to derive the necessary parameters and specifications required.
- **To review, analyze and evaluate the current state of tactile feedback systems.** Literature review of available tactile feedback system to: i) assess suitable candidates, ii) establish the limits of current stage of development, and iii) identify possible improvement to facilitate adoption to intended solution.
- **To design appropriate tactile feedback system to facilitate solution.** Explore and implement tactile sensor to measure normal force and detect localized slip events together with tactile display to replicate grip force as well as slip region growth during slip.
- **To formulate a detailed framework to achieve sufficient grasp transparency.** The main task of the framework is to overcome or mitigate the problem of inherent lag in communication time between remote and local sites.

- **To model incipient slip.** This is required to facilitate the function of the framework.

1.6 Contributions

The following contributions are claimed by this work:

- i. Novel design for incipient slip tactile feedback system.
- ii. Framework leveraging hybrid shared control to mitigate inherent time lag due to remote-local communication.
- iii. Model of incipient slippage to enable prediction.

1.7 Organization

Chapter 2 reviews different literature involving the different tactile feedback systems which have been developed. It describes the specific application with which each of the tactile feedback system was developed for and highlights the paucity of a system catering for efficient grasp. Chapter 3 describes the design and implementation of the incipient slippage tactile feedback system together with the proposed framework to mitigate time delay. Chapter 4 describes the approach undertaken for incipient slip detection consisting mainly of the prototype sensing element and its operating principle. It will also describe the experimental setup built to conduct the necessary experiments. Chapter 5 describes the incipient slip model as well discuss the significance of the results obtained from the experiments conducted. Chapter 6 discusses the approach taken to achieve the objectives set out in Chapter 1 and reiterates whether they have been achieved. The chapter also provides an analysis of those objectives which have not been attained. It also offers suggestions for further work which should be undertaken to improve the system.

Chapter 2

Literature Review

The problems of tissue slip and trauma during grasping or tissue manipulation in the MIS and RMIS settings essentially stem from the inherent loss of tactile feedback and the subsequent degradation to the surgeon's sense of awareness. As observed in prior studies conducted on precision grip with anesthetized digits in Johansson et al. [39] and Johansson & Westling [43], both a higher rate of object slippages and a higher-than-normal average grip force were incurred as a consequence of the absent tactile sensation due to incipient slippage impairing grip force response. In Chapter 1, the research problem stating that there exists paucity in the current inventory with regards to a tactile feedback system which can both detect incipient slip and timely replicate the relevant tactile sensation through slip region growth to elicit the necessary tactile afferent signals for appropriate grip force response was put forward. Henceforth, the purpose of Chapter 2 is to present a critical review of the current state-of-the-art for *complete* tactile feedback systems consisting of a categorical coverage of the important aspects of existing tactile feedback systems developed specifically for the MIS and RMIS settings. It would consequently be shown that though the nature of tactile feedback is complex and intrinsically diverse (e.g. detection fine and rough texture, slips, & forces), extant technology limits the range of tactile sensations of which a tactile feedback system could efficiently replicate. It would also be revealed that there is a dearth of tactile feedback systems targeting the grasping issue in particular and none which purposefully seeks to detect and replicate the dynamics of the stick-slip region during grasping. Coupled with the aforementioned prevailing problems related to grasping within the MIS/RMIS setting, these facts suggest that a need does exist for the development of a tactile feedback system that expressly elicit tactile afferent signals required for maintaining optimal grasp force during grasping. Hence the purpose of this review is important in establishing that need.

2.1 Scope of Review

The purpose of this review is as follows:

- i. To review state of the art of research into tactile feedback systems.

- ii. To organize and classify the different works on tactile feedback system based on the individual application in order to perform a systematic review.
- iii. To clearly show the dearth of work on tactile feedback systems to facilitate grasping and manipulation of tissue.

2.2 Definition and Categorization of Tactile Feedback Systems Reviewed

In the review of tactile sensors conducted by Lee & Nichols [50], the general tactile feedback system had been classified under the broad headings of *teleoperation* and *virtual reality* applications, the main distinction between the two being the need to consider both sensing and reproduction of tactile sensations in the former but only reproduction of tactile sensation in the latter. Owing to the distinct issues encountered in the development of a tactile feedback system within the MIS and RMIS settings, there exists a need to further focus the review beyond this generalized classification entailing a more exacting definition and purpose-driven categorization of the tactile feedback systems intended for reviewing. The following sub-sections will seek to define the tactile feedback systems developed specifically for integration within the MIS/RMIS setting and describe the categorization approach undertaken for the review.

2.2.1 Definition of the Tactile Feedback System within MIS/RMIS

In their review of the important aspects of artificial tactile feedback in laparoscopic surgery, Schostek et al. [29] had established two overarching functions of feedback information within the MIS/RMIS settings: the evaluation of intra-operative findings (e.g. detection of both anatomical and pathological tissue typically through palpation) and grasping and retraction of tissue. In practical terms, to fully or partially deliver the two aforementioned functionalities back to the surgeon operating on either MIS (due to the constrained use of the elongated surgical instruments) or RMIS (due to the inherent physical isolation of master-slave systems) would necessitate both sensing at the remote tissue/instrument interface within the body as well as tactile sensation replication at the surgeon's instrument or master control interface thus harkening back to the aforementioned teleoperation-based tactile feedback system. To that end, both Eltaib & Hewit [51] and Schostek et al. [29] had stipulated the key elements of a complete tactile feedback system as consisting of a tactile sensor at the slave-instrument end, a

tactile display at the surgeon master console end and an overall control unit. The following subsections describe the tactile sensor and display elements of the tactile feedback system in greater detail:

I. Tactile Sensor

The tactile sensor at its most general level has been defined as ‘a device or system that can measure a given property of an object or contact event through physical contact between the sensor and the object’ [51]. The main task of the tactile sensor here lies in measuring the different parameters associated with the contacted object which may include the material characteristics of contacted tissue (e.g. texture, stiffness, shape, temperature, etc.) as well as the contact configuration of the forces on it (e.g. vibration, pressure distribution and impinging force) [52]. The tactile sensor could be classified into two mainstays namely those that seek to ascertain *static* perception of object shape and *dynamic* sensing defined as sensing during motion to obtain perception of high spatial and temporal frequencies crucial for fine surface features/textures and dexterous manipulation [53]. The tactile sensor may rely upon a wide variety of transduction principles (e.g. piezoelectrical, piezoresistive, piezocapacitive, magnetoresistive, optical, ultrasound and mechanical) to quantitatively convert the measurand into viable electrical signals to be delivered and decoded by the control unit. The design of a tactile sensor may include (depending on its intended use) a spatial matrix configuration (e.g. 3 by 2 [54], 10 by 16 [55]) to enable a distributive profile measurement as well as an elastomer-based covering which functions as a compliant surface allowing for (spatial) low-pass filtering, geometric conformity with the contacted surface as well as protection of fragile sensing elements. Other notable design concerns include the overall size of the sensor and extent of the readout circuitry due to the limited size of the surgical entry points (i.e. 5mm or 10mm diameter [32]) as well as the surgical instrument’s contacting interface (typically ranging between 8 mm by 8 mm to a maximum of 8mm by 16mm and possibly exhibiting relief profiles such as sharp jaws or hemispherical features [30]) in addition to sterilizability [56]. The performance of the tactile sensor is typically gauged based on the following parameters: spatial resolution, temporal response, measurand range, accuracy, linearity and hysteresis [57]. Goethals et al. [55] added that ideally, the performance

of the tactile sensor should mimic or at least approach the abilities of the human skin in certain aspects (e.g. conformity, spatial resolution) to facilitate the underlining purpose of the tactile feedback system that is to restore *human* tactile feedback although this would very much depend on the intended function of the tactile feedback system.

II. Tactile Display

In their review of tactile interfaces, Benali-Khoudja et al. [58] had defined the tactile display as a ‘man-machine interface that can reproduce as truly as possible the tactile parameters, such as the texture, roughness, temperature, and shape’. The function of the tactile display here is to replicate the tactile parameters of the object as acquired through the tactile sensor to the person in contact with the display, typically on the fingertips due to its inherently high tactile sensation acuity. Tactile sensations could be generated within humans by stimulating the four different types of subcutaneous tactile afferents on the glabrous skin (i.e. SAI, SAII, FAI and FAII) through either actual physical deformation of the skin (via mechanical [59, 60 & 61] or acoustic means [62, 63 & 64]) or direct electrical stimulation¹ of individual types of mechanoreceptors [67, 68 & 69] associated with each tactile afferent. Tactile displays which rely on physical deformation of the skin typically consists of a mechanical intermediary (e.g. an array of pins, focused ultrasonic waves) that directly impinges on the surface of the skin causing deformation while those that rely on electrical stimulation are made up of small-scale anode-cathode pairs [67] that generate subcutaneous electrical currents. Either display would bank on control signals provided for by the control unit to specify the necessary mechanical torque or current required based on input from the tactile sensor. Unlike the electrical tactile display however, the former mechanical approach may further incorporate an elastomer-based cover to both prevent injury and function as a low-pass filter not dissimilar to the tactile sensor. Important design factors would then include: the stroke length and displacement resolution of the tactors, the amount of force reproduced as well as resolution of force, the density of the tactor array and its

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¹ It is of note that in reviewing the state-of-the-art of tactile displays, Chouvardas et al. [65] had stated that electrical stimulation displays have not been used due to their invasive nature. Monkman et al. [66] had earlier raised concerns with regards to the safety of the *small electrical shocks* present for electrical tactile displays and the need to adopt changes to the current state of legislation for continued research.

temporal response which determines the spatial and temporal resolution respectively. Other design concerns include the overall size of the display which is limited by the mounting area (e.g. 1.8cm by 1.0cm on the da Vinci master control [47]), the size of the contacting array (i.e. size of fingerpad 1-2 cm² [57]) and the need to avoid the human pain threshold of 3.2N force impacting on a skin area 1.75 mm in diameter (equivalent to 1.3MPa) [70]. King et al. [71] further stipulated that the total mass of the display should be below 50g to avoid interference with surgical controls².

Comment on mechanical tactile display classification

Although Moy et al. [72] had earlier classified mechanical tactile displays into strain, stress or shape matching systems, the current inventory of tactile displays based on its utility within the MIS/RMIS setting clearly demonstrates a strong affinity towards the static and dynamic classification based on their intended application similar to the tactile sensors [53]. Tactile displays of the former would consist of those designed for restoring palpation within the MIS/RMIS setting such as [59, 60 & 61] as well as presenting complex spatial patterns on the skin within the field of psychophysical studies [73, 74 & 75] which are generally tactor based and typically express normal indentations on the skin. The latter dynamic classification relate more closely to those developed for studying the reaction of the tactile afferents during dexterous manipulation or slip within psychophysics [76 & 77] and, to a certain extent, the balloon-based tactile display within the ‘Multielement Tactile Feedback System’ [54] developed by UCLA’s Center for Advanced Surgical and Interventional Technology (CASIT) which had been shown to lower normal grip forces during dexterous manipulation. These tactile displays may express lateral motion or force on the skin in addition to normal force.

In summary, a tactile feedback system is defined here as one developed *specifically* to restore full or partial functionalities related to the evaluation of intra-operative findings and/or grasping and retraction of tissue back to the surgeon operating within the MIS/RMIS settings. To achieve this, it would have to consist of the following key components:-

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² This is to avoid the weight of the display to become noticeably different to a surgeon from when he is operating directly with his hands.

- i. Sterilizable tactile sensor at the business end of the surgical instrument able to interface with contacted tissue and provide quantitative measure of material characteristics and/or force configuration limited footprint of below 1cm^2 ,
- ii. tactile display integrated with either instrument handle or control interfacing with the surgeon's fingertips to stimulate the necessary tactile afferents and generate tactile sensation in a controllable manner exerting a force below 1.3Mpa and weighing less than 50g , and
- iii. control unit to decode electrical data obtained from tactile sensor and generate the appropriate signals to control the tactile display.

The following section will describe the categorization approach undertaken for the review:

2.2.2 Categorization of the Tactile Feedback Systems within MIS/RMIS

Although the loss of sense of touch in MIS and RMIS comprises both the loss (or degradation for MIS) of kinesthetic and tactile feedback, comparatively fewer works on restoring the missing tactile feedback has been undertaken when compared to force feedback [47 & 78]. Consequently, the current list of tactile feedback systems is limited to the realm of developmental works within various research facilities and universities. The purpose of a critical review of these prior works is twofold. First is to introduce the current state-of-the-art on tactile feedback systems development for the MIS/RMIS setting. Second is to highlight the overwhelming focus on developing tactile feedback systems to solve the impaired palpation problem related to restoring the *static* evaluation of intra-operative findings functionality as compared to the *dynamic* grasping problem and thus underline the absence of a system that can detect and replicate the phenomenon of growing slip region. In order to highlight the salient features and differences of each of the two aforementioned variations of tactile feedback system developed for enhancing MIS and RMIS, the proposed review will be conducted based on the following categorization approach:

- Static Tactile Feedback System and
- Dynamic Tactile Feedback System.

The motivation behind such a classification is discussed in the following subsections:-

I. Static Tactile Feedback System

The main principle which compels the development of tactile feedback systems within this category is the restoration of the first functionality of feedback information mentioned at the end of Section 2.1.1 pertaining to the evaluation of intra-operative findings. The common objective associated with the restoration of this functionality is the re-enabling of the assistive task of palpation for detection of tumor [2], subsurface arteries [60] as well as diagnosis of the general condition of tissue [61]. The SAI tactile afferent is specifically targeted here due to its eminent role in relaying shape [79], coarse texture [80] and static skin indentation [81] (i.e. sustained force/pressure), all important aspects of the task of palpation. As a consequence, many of the design specifications of the static tactile feedback system, as shown in Table 2.1 below, are based on the characteristic parameters of the SAI tactile afferents. The average design specification for spatial resolution lies between 1 to 2mm and is set to approach, or possibly exceed, the 1.3mm [82] center-to-center distance of the mechanoreceptive endings for SAI tactile afferent units as well as the two-point discrimination threshold of less than 2mm [83 & 84]. This stipulated spatial resolution thus leads to the 10 by 10 to 10 by 16 tactor array whose total contacting area would match the targeted fingerpad area of 1cm² to 2cm² [57]. The stipulated frequency range of between DC to 30Hz for Goethals et al. [85] is set to match the most easily excitable range of the SAI tactile afferent of 2Hz to 32Hz [86] as well as the expected sensations experienced at the observed nominal surgical palpation speed of 120mm/s [87]. The stipulated stroke length of 2mm to 3mm for the tactor pins are a match to the maximum indentation depth of 2mm to 3mm for skin [88]. Force range of between 0.5N to 1N is based on the need for the tactors to support the forces compelled by the surgeon's finger and for maintaining its shape and form during actual surgery [2 & 60]. Finally, the sensor sensitivity of 5kPa to 10kPa represents a compromise based on the observed pressures of between 10kPa to 40kPa when conducting soft tissue palpation [10] while the 10% accuracy exceeds the 14% just noticeable force difference on the fingertip at low frequency [89].

Table 2.1 Design specifications of the static tactile feedback systems

Reference	Goethals et al. [85]	Moy et al. [60]	Howe et al. [2]	Ottermo et al. [61]
Spatial resolution	1mm	1mm	2mm (center to center)	1mm
Size of array	10x16	10x10	-	10x10
Frequency range	DC to 20-30Hz	>50Hz	$\geq 10\text{Hz}$	$\geq 50\text{Hz}$
Stroke	2-3mm	2mm	3mm	3mm
Force range	0.5N/tactor	1N/tactor	$\geq 1\text{N/tactor}$	0.5N-1.0N /tactor
Sensitivity	5-10kPa	-	-	-
Accuracy	10%	10%	-	-

II. Dynamic Tactile Feedback System

The motivation behind the development of dynamic tactile feedback system defined within this category is the restoration of the grasping and retraction functionality as described in Section 2.1.1. The underlying problem which the tactile feedback system seeks to solve is the inability to maintain optimal grip force while grasping or manipulating tissues within the MIS/RMIS setting. Unlike the static variety, the primary target of the tactile feedback system in this category is the FAI tactile afferent due to its crucial role for eliciting apt grip force response when either faced with unexpected external load forces [37] or encountering different contact surfaces [38]. With regards to that, the FAI tactile afferents have been observed to respond to both depth and rate of *changing* indentation [81] corresponding to changes in load force rate critical for grasping tasks and other forms of dexterous object manipulation. It is of note that there is relatively few complete tactile feedback systems that actively seek to reestablish this functionality outside the realm of tactile displays developed for the psychophysical study of dexterous manipulation mentioned earlier [90, 91 & 92], the exception being the ‘Multielement Tactile Feedback System’ [54] developed by UCLA’s Center for Advanced Surgical and Interventional Technology (CASIT) which has been successfully integrated with a working da Vinci RMIS system and tested. The following design specifications from them shown below in Table 2.2 were mainly based on psychophysical studies conducted for optimal Braille displays in addition to data gathered from studies characterizing mechanical response from tissue during robotic laparoscopy. The design specification for spatial resolution was based on Standard American Braille’s

stipulation of 1.45mm diameter size and 0.89mm spacing for optimal hemispherical Braille dots [93]. The array size of 3 by 2 was from a similar stipulation for optimal Braille dot groupings. The stipulated 5 to 10Hz frequency range was obtained based on a study conducted to quantify surgical grasping mechanics within laparoscopy [94]. Similarly, the 0 to 5N force range was matched to grasping forces reported in the aforementioned study as well as two others [93, 94 & 95] during tissue manipulations in surgery.

Table 2.2 Design specifications of the Multinodal Tactile Feedback System

Reference	Culjat et al. [47]
Spatial resolution	2.34mm (center to center) 0.89mm (edge to edge)
Size of array	3x2
Frequency range	5-10Hz
Force range	0-5N

Comment on the spatial resolution and frequency design specification

It is essential to note that the spatial resolution specified here was based on studies conducted on Braille displays while the frequency range was derived from the measured frequency of grip force variance encountered on the surgical instrument handle as observed in [93] (i.e. the number of times the fingertip gripped and relaxed on the handle) rather than actual parameters related to the slip events which occur on the tissue/instrument interface. With regards to the spatial resolution, actual density of the targeted FAI tactile efferent mechanoreceptor endings measures at 140 units/cm² which leads to a center-to-center distance of 0.9mm on the fingertips [82]. It is also pertinent to recall the more exacting perimeters for slip detection and grip force response as observed in the studies conducted on precision grip [37, 38, 39 & 40] mentioned in Section 1.3 in which grip force response initiates within 74-84 ms [37 & 38] post-slip with more than half the FAI tactile afferents measured responding by 8 ms [38]. These performance indices coupled with the FAI tactile afferent high operating frequency range of 8 to 200Hz (most easily excited range of 8 to 64Hz) [86] therefore hint at a higher frequency and more stringent spatial resolution specifications for the dynamic tactile feedback than stipulated above.

It is therefore clear that the main difference between the static and dynamic categorizations of tactile feedback systems undertaken within this review lies in the design specifications which deviate due to the divergence in their intended functions i.e. restoration of evaluation of intra-operative findings and grasping and retraction of tissue functionalities. In summary the static tactile feedback system targets the SAI tactile afferents and is composed of static tactile sensor with tactile displays which focus on high spatial resolution while the dynamic tactile feedback system targets the FAI tactile afferents and requires dynamic tactile sensor with a more demanding frequency specification.

2.3 List reviewed

The following five tactile feedback systems were reviewed:-

1. Howe et al.'s Remote Palpation System [2],
2. Moy's Bidigital Teletaction System [60 & 96],
3. Ottermo et al.'s Virtual Palpation Gripper [61],
4. Goethals' Tactile Feedback System for RMIS [65] and
5. King et al.'s Multinodal Tactile Feedback System [54].

The five represent the list of complete tactile feedback systems developed for the MIS/RMIS setting. The first four represents the static category while the fifth and final one represents the sole representative within the dynamic category. The review will describe the main components of the system namely tactile sensor and tactile display along with the validation tests undertaken. It will compare the performance of each individual component as well as the entire system as a whole and assess whether they are fit for restoring the grasping functionality.

2.3.1 Howe et al.'s Remote Palpation System: 8 by 8 capacitive tactile sensor linked to 6 by 4 shape memory alloy display for palpation [2]

The Remote Palpation System developed by Howe et al. [2] at Harvard University describes a complete tactile feedback system designed to replicate the pressure distribution at the contact interface located on the remote tip of the surgical instrument onto the operating surgeon's fingertips in order to facilitate the palpation task for locating subsurface tissue or tumor. The complete system consisted of a

static 8 by 8 capacitive tactile sensor array linked to a 6 by 4 shape memory alloy (SMA)-based small-scale shape display. The idea behind the system is for it to be packaged as a fully integrated surgical instrument with which the surgeon could insert via a trocar and utilize as a probe. The tactile sensor at the tip of the instrument would measure the distributed pressure on the area of contact and relay the signal to the control unit which would then activate the shape display to replicate the measured pressure distribution onto the glabrous skin of the operator's index finger. A test simulating the localization of tumor was conducted to ascertain the effectiveness of the system. The following sub-sections will describe the tactile sensor, small-scale shape display and the test conducted in greater detail.

I. 8 by 8 static capacitive tactile sensor array

The static capacitive tactile sensor array is based on an earlier design by Fearing [97] and features two crossed-layers, each consisting of 8 copper wires, with the top layer supported by thin strips of silicone-based material resulting in 8 by 8 tactile sensing elements, each element being a cross-section of the orthogonal top and bottom copper wires with the air in between acting as the dielectric as shown in Figure 2.1. Each element is separated from the other by an edge to edge distance of slightly over 0.25mm and measures an effective area of approximately 1.5mm by 1.5mm with a dielectric thickness of 0.13mm. The entire sensor was then encapsulated by a layer of elastomer of variable thickness which allows for varying the surface compliance to suit the intended area of application [2]. The main principle of transduction is capacitive in which force impinging on the top surface of a particular element of the tactile sensor array closes the effective distance between the copper layers thereby increasing the capacitance value of the particular element. The pressure distribution could then be obtained through measuring the individual capacitance at each element which allows for a spatial pressure profile to be built. Each sensor element's useful sensing range extends to over 2N with a reported noise level of less than 0.001N. The electronic readout is designed to deliver power to as well as to receive capacitance output from each element of the sensor within the 5ms. This readout speed gives a maximum frequency of 200Hz to the sensor. The spatial resolution could be inferred from the response of a single element to an impinging rounded 1.5mm diameter probe which results in a

gaussian-like spatial impulse response with standard deviation of 0.96mm [98]. However, Pawluk [99] added in the same report that the resolution would be coupled to the neighboring elements in which an element in the same row and column would contribute to less than 8% and those diagonal less than 1% of the measured pressure.

Figure 2.1 8 by 8 capacitive tactile sensor (adapted from [57])

II. 6 by 4 SMA-based small-scale shape display

The tactile display consists of 24 individual pins configured in a 6 by 4 array and made up of 4 stacks of a row of 6 each as shown in Figure 2.2A. The pins are spaced approximately 2.1mm center-to-center thus providing a spatial resolution of 2.1mm. The principle mode of actuation consists of a SMA wire 30mm long and 0.075mm in diameter with one end connected to the rigid frame and the other to a lever which in turn supports the pin as shown in Figure 2.2B. Actuation is realized through heating the wire with electrical current which results in an increased tension that rotates the lever about the fixed shaft. The lever then raises the supported pin up to the desired height with a maximum limit of 3mm. When the wire cools down, the spring provides a restoring force to return the pin to its original position. The display has an operational bandwidth approaching 10Hz with the -3dB point lying between the 6 and 7Hz and generate an amount of force equivalent to at least 1N/element [99]. The frequency performance was attained despite the slow rise and fall time of the SMA wire's thermal actuation through the introduction of a large derivative term to the control and an active air-cooling system respectively. A closed loop proportional position control was implemented to overcome the large hysteresis experienced by the wire.

Figure 2.2 A. 6 by 4 SMA-based shape display. B. Cross-section displaying working principle of each pin (adapted from [99]).

III. Localization of tumor test

The complete tactile feedback system was integrated onto an in-house force-reflecting 2DOFs teleoperated hand system (see Figure 2.3) to evaluate its performance. The tactile sensors were placed on the ‘finger tips’ of the slave-hand. Three subjects were requested to locate a hard rubber cylinder measuring 4mm in diameter simulating the tumor which was hidden from view 5mm beneath a block of foam in a series of 60 trials. The vertical location of the foam was varied upwards or down in between trials within a range of 20mm using a translational stage. Although the subjects were prevented from seeing the block of foam, the trials were conducted with a single row of the tactile sensor and tactile display activated together with the system’s in-built force feedback. The results showed that in over 50% of the trials conducted, the subjects were able to locate the ‘tumor’ within an error of 1mm. This improved by 45% when the error restriction was increased to within 3mm. In contrast, the absolute error was measured at 13mm without the tactile feedback system [2].

Figure 2.3 2DOF force-reflecting teleoperated hand system (adapted from [100]).

2.3.2 Moy's Bidigital Teletaction System: 4 by 8 cylindrical capacitive tactile sensor linked to 5 by 4 by 5 subsurface strain inducing pneumatic tactile display for teletaction [60 & 96]

Moy [96] developed the Bidigital Teletaction System to transmit information about a subsurface pulsing blood vessel. The complete system consisted of a static 4 by 8 cylindrical capacitive tactile sensor array linked to a hexagonal 5 by 4 by 5 subsurface strain inducing pneumatic tactile display integrated onto a surgical grasping instrument. The idea is to allow the surgeon within an MIS setting to utilize the instrument similar to a grasper as seen in Figure 2.4 allowing the surgeon to feel the contact surface on his fingertips similar to what he would have experienced in a conventional open surgery through gloved hands of 2mm thickness (refer to Figure 1.1, pg. 3). A test was conducted using silicone tubing placed beneath a silicone gel-based wrap to simulate detection of blood vessel embedded within tissue. The following sub-sections will describe the tactile sensor, small-scale shape display and the test conducted.

Figure 2.4 Schematic diagram of the Bidigital Teletaction System (adapted from [96])

I. 4 by 8 cylindrical static capacitive tactile sensor array

The tactile sensor features two crossed-layers of copper wires each measuring 1.5mm wide and 0.15mm thick as shown in Figure 2.5 below. The top layer consists of 8 copper wires running horizontally while the bottom layer consists of 4 copper wires running vertically as the drive and sense lines respectively. Each cross-section represents a sensing element featuring a 2.7mm center-to-center distance, a dielectric thickness of 0.13mm and a 2mm elastomer-based anti-aliasing layer. The entire assembly was configured around a plexiglas cylindrical core measuring a total diameter of 32mm and height of 25mm which simulates the human finger. The main principle of transduction is capacitive in which force impinging on the surface of a particular element of the tactile sensor array reduces the effective distance between the copper layers thereby increasing the capacitance value of the particular element. The aim of the tactile sensor is to measure the strain experienced beneath the elastomer layer as described by Fearing in [97]. The tactile sensor runs at an operating frequency of 100Hz.

Figure 2.5 4 by 8 cylindrical static capacitive tactile sensor (adapted from [96])

II. 5 by 4 by 5 Hexagonal configuration pneumatic tactile display

The tactile display consists of 14 individual pins in a 5 by 4 by 5 configuration that conforms onto the fingertip as shown in Figure 2.6. The pins, spaced approximately 2mm center-to-center, are each inserted into individual silicone tubings. The top of pins (i.e. interfacing the skin of the fingertip) were covered with a 0.5mm membrane layer which functions as the main mechanical transducer (i.e. allowing the transfer of mechanical force onto the skin of the fingertip) enabling a 10% amplitude resolution to be sufficient [54]. The aim of the tactile display is to generate the same normal subsurface strain as would be experienced by the hand covered with 2mm of the same elastomer material. The actuation is effected through pneumatically by feeding high pressure air into the tubings, each connected to a PWM-controlled solenoid valve and activated by Siemens C167CR-LM microprocessor. This allowed for a 128-level linear force control ranging from 0 to approximately 241kPa. However, Moy [96] reported that the 150Hz operating frequency of the PWM resulted in perceptible buzz (i.e. noise) measuring 38kPa peak to peak. Although the individual solenoid valve exhibited a consistent rise time of approximately 2ms when switched on, the overall display's 3dB point was reported at 5Hz operation frequency [60]. Although no definite spatial resolution was forthcoming, Moy et al. [72] had calculated based on the psychophysical

experiments he conducted that the display should be able to convey a 4mm period grating with 4N applied force.

Figure 2.6 5 by 4 by 5 Hexagon pneumatic tactile display (adapted from [96])

III. Detecting subsurface artery

The Bidigital Teletaction System, as shown in Figure 2.4, was evaluated by simulating detection of pulsating blood pressure within an artery located beneath a layer of tissue. The simulated artery was a silicone tube with an outer diameter of 2mm which was placed within a 2mm deep trench covered with silicone gel covering a planar area of 50mm by 50mm. The blood pressure was simulated pneumatically with 8 different air pressures ranging from 0 to 241kPa in steps of 34.5kPa. The test consists of ascertaining the threshold peak pressure for each of the ten subjects by running a ‘Staircase-method’ test which consists of randomly increasing the introduced pressure until the subject detected it or decreasing the pressure until detection was lost. The 64 trials were conducted once through with the ten subjects using the system and repeated a second time with five subjects directly touching the simulated artery with 2mm gloves and the results were subsequently compared. Although Moy [96] had reported that the resulting threshold measured were quantitatively better through direct touch, the difference between the two thresholds obtained were not significant at 90% confidence.

2.3.3 Ottermo et al.'s Virtual Palpation Gripper: 15 by 4 pressure capacitive tactile sensor array linked to 8 by 4 micromotor-actuated small-scale shape display for palpation [61]

The Virtual Palpation Gripper was developed by Ottermo et al. [101] of the Norwegian University of Science and Technology to replicate the shape, hardness and size of the contact interface located on the remote tip of the instrument onto the operating surgeon's fingertips to facilitate palpation task for locating subsurface tissue or tumor. The complete system consisted of a commercially available TactArray 15 by 4 pressure capacitive tactile sensor array from Pressure Profile Systems (PPS) Inc. linked to an 8 by 4 micromotor-actuated small-scale shape display and was successfully integrated onto an Olympus A6998 grasper. A test simulating the localization of tumor was conducted to ascertain the effectiveness of the system. The following sub-sections will describe the tactile sensor, small-scale shape display and the test conducted in greater detail.

I. 15 by 4 PPS TactArray pressure sensitive capacitive tactile sensor array

The tactile sensor was a customized TactArray pressure sensitive capacitive tactile sensor commercially available from Pressure Profile Incorporated which features a 15 by 4 array of capacitive elements in a thin continuous sheet measuring 3.5cm by 1cm by 2mm. The conductive material utilized in TactArray was soft and flexible enabling it to be mounted and conformed onto the lower jaw of the Olympus A6998 grasper as seen in Figure 2.6 below. The sensor measures pressure with an effective range of 0 to 70kPa at a frequency of 1kHz [101] and a spatial resolution of 2mm.

Figure 2.7 15 by 4 TactArray pressure sensitive, capacitive tactile array mounted on the lower jaw of an Olympus A6998 grasper (adapted from [101])

II. 8 by 4 micromotor actuated tactile display

The tactile display consists of 32 individual pins in an 8 by 4 configuration as shown in Figure 2.8, each with stiffness measured at 50N/mm. The entire display measures 27mm by 20mm by 18mm. The tactor measures up at 2.6mm in diameter and are spaced 2.7mm apart. The top of surface of the display was covered with a protective layer of silicone rubber measuring 0.5mm as seen in Figure 2.8A. The positioning resolution was implied to be 20 μ m theoretically with an accuracy determined to be approximately 40 μ m. Each of the 32 tactors was actuated by an individual SLB-06H1PG79 micro brushless motor commercially available from Namiki Precision Jewels. Each motor was individually controlled through a driver circuitry consisting of 5 cards (each controlling 8 motors) stacked vertically into a single block measuring 34mm by 34mm by 45mm. The display was able to effect 0.4N to 0.5N of force at a frequency of 0.7Hz at full extension of 3mm. The aim of the tactile display is to display shape, hardness and size of the contacted object onto the glabrous skin of the surgeon's index fingertip.

A. Top view of 8 by 4 tactile display

B. Tactile display as mounted onto Olympus A6998 grasper

C. Schematic of display housing

Figure 2.8 A. Top view of 8 by 4 tactile display. B. Tactile display as mounted onto Olympus A6998 grasper. C. Schematic of display housing (adapted from [61])

III. Detecting subsurface artery evaluation

A series of test was conducted to gauge the ability of the Virtual Tactile Gripper in relaying tactile information pertaining to shape, hardness and size of the contacted object. The experiment consisted of ranking 5 different balls placed within finger cots filled with water and ultrasound gel (to simulate the slippery interior of the intestine) based on hardness and size using the virtual tactile gripper and a standard laparoscopic grasper. The setup was designed to mimic the actual laparoscopic surgery with the test objects hidden from view within a box, the graspers introduced into the box through holes simulating surgical incision/trocar interface as well as visual feedback provided by a camera. In a comparison between laparoscopic grasping with a conventional gripper and the virtual tactile gripper through the setup, the difference in performances in the test for ranking of hardness was not significant while that for the results in the test for ranking of size was significant based on errors in rank judgements committed at the 5% confidence level. However, there were more errors committed using the virtual tactile gripper than with a conventional gripper.

2.3.4 Goethals' Tactile Feedback System for RMIS: 16 by 16 elastoresistive tactile sensor array linked to 8 by 4 micromotor actuated tactile display for RMIS [85]

In his dissertation, Goethals [85] alluded to the enabling of the palpation task as the main focus of the Tactile Feedback system for RMIS in emphasizing the importance of palpation during MIS as well as in the design specifications targeting SAI receptors and small-scale shape perception. The system consists of a 16 by 16 elastoresistive tactile sensor array and an 8 by 4 tactile display integrated together into a purpose-built surgical instrument which could achieve ingression via the trocar, quantitatively measure the tactile parameters related to shape, size and hardness of the contacted tissue and display the said parameters onto the surgeon's glabrous skin of the index fingertip. To ascertain the effectiveness of the system, a test was conducted to gauge a user's ability to interpret the size of the contacted object.

I. 16 by 16 elastoresistive tactile sensor array

The tactile sensor consists of an elastoresistive material configured into a 16 by 16 element array with a spatial resolution of 1mm [55]. The tactile sensor has an effective area of 16mm by 16mm and is covered by 0.5mm rubber sheet which allows for a more gradual inter-element measurement [85]. The main transduction principle relies on elastoresistive material which exhibits a piezoresistive behavior in which increasing force reduces the effective resistance. The matrix arrangement of electrodes into columns and rows allow for 16 discrete measurements of resistance thus allowing a distributive pressure profile to be described through measuring the resultant voltage of individual row/column element. Two multiplexers are utilized, one to connect input voltage to a specific column and the other to connect a specific row to the resistance bridge where the output voltage could be measured. To prevent crosstalk between neighboring elements, the output voltage is fed back to all non-activated rows and columns. The tactile sensor offers a resolution of better than 4kPa or 0.04N/element and an operating frequency of 78Hz. Figure 2.9 below shows the prototype tactile sensor mounted on the cylinder used for testing.

Figure 2.9 Prototype of 16 by 16 elastoresistive tactile sensor (adapted from [55])

II. 8 by 4 micromotor actuated tactile display

The tactile display as seen in Figure 2.10 consists of 32 individual pins, each pin consisting of a hardened steel dowel measuring at 0.6mm in diameter, in an 8 by 4

configuration with a spatial resolution of 2mm as shown in Figure 2.8. The entire display measures at 17mm by 18mm by 6mm weighing in at 6g. Each pin is pneumatically actuated and controlled individually with commercial valves which could proportionally regulate the input pressure allowing for an output force of 0.47N per pin. The effective frequency is less than 20Hz beyond which the built-in control of the valves could no longer follow the input signals from the control unit. The valve assembly measuring at 82mm by 50mm by 15mm is located off-site and is connected to the display by vinyl tubes. The 32 valves are controlled by a Labview card with 4 sample-and-hold components, each capable of interfacing with 8 of the valves.

Figure 2.10 Prototype of 8 by 4 pneumatically actuated tactile display (adapted from [85])

III. Evaluating size of different cylinders

The test conducted to evaluate the effectiveness of the tactile feedback system consists of determining the correct ranking of 5 separate cylinders of differing diameters based on size. Due to the inability of the system to be fully integrated onto a single surgical instrument, the tactile sensor was instead mounted onto a cylinder which was then manipulated by the experimenter as seen in Figure 2.11 while the test subjects interfaced with the tactile display without being able to see the test set-up. As the array size of the tactile sensor and the tactile display did not match, only the 16 by 8 center elements of the tactile sensor were utilized. The square of the readings of 2 elements were averaged to provide an overall 8 by 4 tactile image that matches with the tactile display. The diameters of the 5 cylinders measure at 90mm, 63mm, 41mm, 31mm and 25mm respectively whereupon each cylinder of a particular diameter was paired with another of a unique diameter. Each

trial then consisted of each of 5 subjects being asked to determine which of the two cylinders presented sequentially was of a superior diameter. Each coupled cylinder was presented twice with the order of cylinder presentation reversed. The results show that although the ability to discriminate with the tactile feedback system was significant to guessing for all the couples, the correct results for each of the cylinder couple tested numbered more than 10 out of 20.

Figure 2.11 Manipulation of tactile sensor by experimenter (adapted from [85])

2.3.5 King et al.'s Multinodal Tactile Feedback System: 3 by 2 elastoresistive tactile sensor array linked to 3 by 2 balloon-based pneumatic tactile display for RMIS [54 & 102]

King et al. [54] developed a multi-nodal tactile feedback system which was successfully integrated to a da Vinci RMIS for the purpose of grip force and tissue slippage reduction during tissue manipulation. The system consisted of 3 by 2 tactile sensors mounted onto the flat inner surface of a Cardiere grasper's upper and lower jaws (each area measuring 14mm by 5mm) connected to two 3 by 2 balloon-based tactile displays, each placed on the 1.8cm by 1.0cm mounting area on the da Vinci master controls to interface with both the index and thumb of the surgeon. Two tests were conducted to test the effectiveness of the system developed: i) a peg transfer test and ii) tissue manipulation test. The following sub-sections will describe the tactile sensor, small-scale shape display and the test conducted in greater detail.

II. 3 by 2 elastoresistive tactile sensor array

The tactile sensor consisted of a modified commercially available Tekscan A201 FlexiForce piezoresistive force sensor which features a thin-film profile (thickness measuring 200 μ m), small sensing area (10mm in diameter) and a maximum force range of 0N to 110N. The sensor is configured into three layers which include a piezoresistive Thin Film Piezo (TFP) layer, a silver conductive layer and an insulation layer. The main transduction principle is piezoresistive based upon the TFP layer, a polyimide-based, carbon-filled paste developed from Electro Science Laboratories (ESL RS15114) which experiences reduction in its effective resistance with increased impinging force on its surface. A 3 by 2 array of gold electrode pad, each measuring 1.75mm by 1.75mm and separated by a 1.5mm space (to prevent crosstalks), functions as the effective sensing element. By obtaining the measuring the output voltage at each of the element, the resistance could be derived thus allowing for the pressure distribution to be constructed [54]. The electrode pads along with the ancillary connections were constructed upon a 127 μ m thick polyimide film through a series of microfabrication processes before being glued onto the piezoresistive TFP layer. The analogue voltage signal derived from the sensor goes through a signal conditioning board (which limits the sensor voltage to a maximum of 3V to protect the DSP) before relaying it the digital signal processor (DSP). The onboard ADC then converts the analogue voltage signal into digital before the control algorithm segments the voltage into the following 5 determined ranges: i) 0V to 0.7V, ii) 0.7V to 1.3V, iii) 1.3V to 1.9V, iv) 1.9V to 2.5V and v) 2.5V to 3V. The response time of the tactile sensor measures at less than 5 μ s with each element limited to measuring from 0 to 10.7N due to the limited voltage output [47]. Figure 2.12 below shows the tactile sensor mounted on both the upper and lower jaw of the Cadiere grasper.

Figure 2.12 3 by 2 piezoresistive tactile sensor (adapted from [47])

II. 3 by 2 balloon-based tactile display

The tactile display measures at 18mm by 10mm by 4mm and weighs in at 0.65g. It is composed of a polydimethylsiloxane (PDMS) substrate which houses the 6 pneumatic channels arranged in a 3 by 2 array vertical configuration measuring at 3mm in diameter each linked to 6 horizontal channels measuring at 2mm in diameter [36]. The top surface of the substrate was coated with a 300 μ m thick spin-coated silicone film (Smooth-On, SORTA Clear 40) to form the 3mm balloon-based tactator on top of the 6 vertical channels, each having an edge-to-edge spacing of 1.5mm. Each balloon is pneumatically inflated with SMC ITV0010-2MMS pressure regulators which provide proportional pressure input ranging from 0 to 103.4kPa in increments of approximately 7kPa. The control algorithm onboard the DSP determines the amount of pressure by outputting PWM signal that match the 5 range segment of the tactile sensor i.e. segment i) results in 0% duty cycle, segment ii) results in 25% duty cycle, segment iii) results in 48% duty cycle, segment iv) results in 72% duty cycle and segment v) results in 100% duty cycle. The PWM signal is then fed through the signal conditioning board which converts it into an analog DC signals to be relayed to the pressure regulators. The display features a response time greater than 93ms, is able to deflect a maximum of 1.5mm and exerts a large total force output of more than 2N. The display spots a Velcro strap which is used to secure the display onto the surgeon's finger as seen in Figure 2.13.

Figure 2.13 3 by 2 balloon-based pneumatic tactile display (adapted from [103])

III. Evaluating performance through the peg and tissue manipulation tests

Two tests were conducted to test the effectiveness of the system developed: i) a peg transfer test to test the effectiveness in reducing grip force and ii) tissue manipulation test. The peg transfer test was derived from the standard peg transfer test described in the Fundamentals of Laparoscopic Surgery (FLS) education module defined by the Society of American Gastrointestinal Endoscopic Surgeons (SAGES) [104]. The test involved 20 subjects consisting of 16 novices and four experts who were tasked to transfer three rubber pieces between two parallel rows of pegs using his or her dominant hand as seen in Figure 2.14. The tasks were broken into three blocks where all three blocks except the middle were conducted without the multimodal tactile feedback system switched on. The results show that the mean grip force utilized when the tactile feedback system was switched on (6.4N) was significantly lower than when the system was inactive (15.3N) [28]. For the second test, the tactile sensor was modified to a single monolithic sensor rather than an array while the six tactors on each of the two tactile displays assigned to each hand were set to inflate together rather than individually. Four subjects consisting of a novice, a surgical resident, a laparoscopic MIS fellow and an expert in robotic surgery were tasked to perform robotic manipulation on a tissue phantom. The phantom was augmented with a pressure indicating film (Fuji Prescale Film LLLW) which would exhibit a darker shade of red commiserate with the pressure exerted. Similar to the peg transfer task, the task was broken into three blocks with only the middle block augmented with the tactile feedback system. The results

showed that there were qualitatively more red marks with higher color intensity observed on the phantom when manipulated without the tactile feedback.

Figure 2.14 Parallel peg transfer test (adapted from [103])

2.4 Chapter Summarization

This Chapter has reviewed five examples of tactile feedback systems developed specifically for the MIS and RMIS settings. The first four systems reviewed were successfully categorized into static while the final system was categorized within the dynamic category as defined in Section 2.2.2. To reiterate, static tactile feedback systems generally seek to restore tactile feedback for the evaluation of intra-operative findings functionality of feedback information while dynamic systems seek to restore for the grasping and retraction function. Table 2.3 presents a summary of the five systems reviewed:

Table 2.3: Summary of review findings

Tactile Feedback System	Tactile Sensor				Principle of transduction	Tactile Display					Category	
	Array size	Spatial resolution	Time response	Range		Array size	Spatial resolution	Operating frequency	Stroke/ Deflection	Force		Actuation principle
Howe et al.'s [2] Remote Palpation System	8 by 8	2mm	5ms	0-2N (element)	Capacitive	6 by 4	2.1mm	10Hz (-3dB between 6 & 7Hz)	3mm	Not stipulated	SMA wire	Static
Mov's [96] Bidigital Teletaction System	4 by 8 (cylindrical)	2.7mm	10ms	1.1N (element)	Capacitive	5 by 4 by 5	2mm	5Hz	Not stipulated	Not stipulated	Pneumatic	Static
Ottermo et al.'s [61] Virtual Palpation Gripper	15 by 4	2mm	1ms	0-70kPa	Capacitive	8 by 4	2.7mm	0.7Hz	3mm	0.4N to 0.5N (per tactor)	Micromotor	Static
Goethals' [85] Tactile Feedback System for RMIS	16 by 16 (effective 16 by 8, cylindrical)	1mm	13ms	0.04N (element)	Elastoresistive	8 by 4	2mm	<20Hz	Not stipulated	0.47N (per tactor)	Pneumatic	Static
King et al.'s [54] Multimodal Tactile Feedback System	3 by 2	1.5mm (edge to edge)	5µs	0 to 10.7N (element)	Piezoresistive	3 by 2 (balloon)	Not stipulated	10.75Hz	1.5mm	2N (total force)	Pneumatic	Dynamic

Table 2.3 shows the main performance parameters relating to each of the tactile feedback system reviewed. In general, all the tactile feedback systems reviewed

observed some common elements such as the utilization of an elastomer layer at both the tactile sensor and tactile display interface. It was also observed that tactile sensor performance parameters tend to exceed those of the tactile display as observed in [83]. The main reason for this lies in the difficulty to scale actuators in order to achieve the demands on spatial resolution. Within the static category of tactile feedback systems, those that seek to replicate shape such as the Howe's Remote Palpation System, Ottermo's Virtual Palpation Gripper and Goethals' Tactile Feedback System for RMIS tend to focus on position control typically stipulating the ability for each tactor to exert a minimum force just sufficient to support the surgeon's finger i.e. around 1N. Moy's Bidigital Teletaction System bucks the trend by seeking to match the subcutaneous strain generated when palpation is conducted with gloved hands in an open surgery.

In addition, the review shows that only the Multinodal Tactile Feedback System could be classified under the dynamic category in seeking to restore the grip and manipulation functionality. It is important to note that even though the achieved operating frequency of 10.75Hz does not stand out, the system was able to achieved genuine reductions in the tactile grip force as compared to operating without the tactile feedback system. The distinct balloon-based tactor is indelibly distinguished from the rest of the tactile feedback systems reviewed in that it replicates the expansion and contraction of the contacting surface characteristic of the local slips critical to grip response as described earlier in Section 1.4. Consequently, it could be surmised that this unique form of tactile stimulation played an important role in the reduction of mean grip forces. However, it is hard to miss that the tactile sensing component still very much mimics the sensing approach of tactile feedback systems in the static category without any overt attempt to detect actual slips occurring at the contact interface of the Cardiere gripper jaw and the grasped object.

In summary, the following conclusions can be made with regards to the aim of this Chapter as stated in Section 2.1:

- A concise and succinct review of the current state-of-the-art on tactile feedback systems along with a summary of the main points have been undertaken in which the target tactile feedback system is defined as having a tactile sensor on the slave instrument contact surface and a

tactile display interfacing with the operating surgeon at the master console and the current inventory could be classified as either *static* or *dynamic* for those that seek to fully restore the palpation and grip tasks respectively,

- With the Multinodal Tactile Feedback System being the sole representative within the dynamic category of tactile feedback system, it has been shown that the current state of tactile feedback system development is heavily skewed towards the static category and,
- A tactile feedback system which could detect slip occurring at the contact surface of the instrument and grasped object and then replicate the same phenomenon on the surgeon's finger is still absent within the current inventory of tactile feedback systems designed for the MIS and RMIS settings.

Chapter 3

Incipient Slippage Tactile Feedback System and Framework

To reiterate, the objective of this work is to develop a tactile feedback system-based solution for achieving grasp transparency in RMIS to preserve natural grip response within the following scope:

- To characterize and ascertain the necessary parameters and events required during grasping of object.
- To review, analyze and evaluate the current state of tactile feedback systems.
- To design appropriate tactile feedback system to facilitate solution.
- To formulate a detailed framework to achieve sufficient grasp transparency.
- To model incipient slip.

While the parameters related to human grasping has been touched on in the first Chapter, the review in Chapter 2 related to the second point above has brought to the fore the absence of a tactile feedback system able to both detect incipient slips and replicate the appropriate tactile sensation that could account for the impediment to natural grasping in RMIS. In that regard, the detrimental effects of limited haptic feedback to task performance in teleoperation has been attested to in both general application [105] and in RMIS (refer to end of Section 1.3). In response to the gap in technology, a new tactile feedback system is proposed in this work and will be described in this chapter coinciding with the third and fourth points above. While implementation of seamless integrated incipient slip detection at the slave and tactile feedback replication for the tactile feedback system remains paramount, a control framework featuring a novel shared control architecture comprising elements of both input-mixing and haptic shared controls [106] is proposed to overcome the inherent time delay resulting from communication/computation lag to achieve the primary objective of more natural grasping. The overall solution to the problem of impeded natural grasping solution within RMIS therefore features an approach to provide for sufficient transparency in precision grasping through

implementation of the novel incipient slippage tactile feedback system with shared control architecture.

This chapter is divided into two parts. The first part systematically describes the different components of the tactile feedback system (i.e. tactile sensor, tactile display and control) consisting of the operating principle as well as the flow of information to effect detection of localized slip, measurement of grip and replication of the necessary tactile feedback. The second part describes the overall principle of the proposed framework and its constituent modules. It also focuses on the formulated approach to resolve the issue of time delay endemic to the telerobotic setup. Section 3.1 illustrates the design of the proposed tactile feedback system in its entirety as well as the working principles scheme formulated to restore the necessary tactile feedback for optimal grasping onto the surgeon's fingertips. Section 3.1.1 identifies the main principles of transduction for both the Center of Pressure (CoP) sensor and Slip Sensor and how they are to be utilized in tandem to measure grip force and detect slip. Section 3.1.2 will cover the tactile display focusing on the actuation principles utilized to affect both normal force and slip replications. The overall framework for mitigating time delay is described in Section 3.2. Section 3.3 will summarize the main points of the chapter.

3.1 Proposed Tactile Feedback System

The objective of the proposed tactile feedback system is to restore tactile sensations connected to incipient slippage occurring on the remote contact surface of the object grasped. The system is primarily three components: tactile sensor to detect incipient slippage and tactile display to replicate the necessary tactile sensations, in which the individual functions of the two elements are to be integrated seamlessly under a singular controlling element, the third element. The tactile feedback system comprises the mainstay of the solution to impeded natural grasping within RMIS and is to be implemented under the aegis of the aforementioned shared control framework. The three components will be described in detail within the following subsections.

3.1.1 Tactile Sensor

In order to restore the grasping and manipulation functionality as mentioned in Section 2.2, the proposed tactile feedback system is required first to be able to

accurately measure exerted forces as well as detect the characteristic localized slip events leading up to an overall slip, the source of both being at the contact interface of the slave instrument during actual grasping or manipulation of tissue. The following section delineates the required performance as well as the assumptions undertaken for the sensor to detect localized slip which will be the primary focus of this work:

Assumption:

1. That curvature along a single axis is sufficient to generate favorable force distribution (i.e. larger magnitude in the middle which tapers off at the periphery, see Figure 4.1).
2. That such distribution would be present to scale based on the size of the curvature.

Required performance:

1. Response to slip must be less than 100 ms [120 & 124] (i.e. the human response).
2. Power demands should be low.
3. Frequency response of at least 700Hz [124].

In order to fulfill the two quintessential requirements as well as conform to the tight space and profile constraints of the contact end of the surgical instrument where the sensors are to be mounted as mentioned earlier in Section 2.2, the tactile sensing component of the proposed tactile feedback system would consist of an integration of the following two tactile sensing elements first demonstrated by Teshigawara et al. [48]: i) the Center-of-Pressure (CoP) Sensor [107] tasked to measure the total force and ii) the Slip Sensor tasked to ascertain slip [108]. Both the CoP and Slip sensors rely upon a pressure conductive rubber layer as the main element for effecting principle transduction which affords both sensors the advantages of a slim profile as well as minimal electrical readout typical of pressure conductive rubber based sensors [85]. The following subsections will describe the CoP and slip sensors in greater detail.

CoP Sensor

The CoP sensor was first proposed by Ishikawa & Shimojo [109] as a means to measure two-dimensional load distribution as mentioned in [110]. As seen in Figure 3.1, the sensor composes of three layers stacked one on top of another: a top layer of conductive film with a pair of electrodes S_1 and S_3 on opposite sides, a middle thin film of pressure conductive rubber and a bottom layer of the same conductive film with a second pair of electrodes S_2 and S_4 located on the orthogonally-oriented sides as opposed to the top layer's electrode orientation. With regards to the size of the sensor, the version developed by Shimojo et al. [107] specifically to obtain the zero moment point (ZMP) of a biped robot measured 42mm by 46mm in area with a total thickness of 0.7mm although one with a reduced size could be fabricated to accommodate a smaller mounting area. The two conductive layers were made from a polymer-based, conductive material coated film with a thickness measuring in at 125 μ m. The electrical readout circuit is tasked with maintaining a constant applied voltage V_0 applied through resistors R_0 as well as receiving the input voltage difference between each pair of electrodes on each layer (i.e. S_1 and S_2 , S_3 and S_4) from which both the location along the x and y-axis and the magnitude of the normal force could be determined. In [111], Gunji et al. had reported that the sensor was able to achieve a high speed response of 1ms due to its simple configuration. The following sections run through the operating principle and performance of the CoP sensor.

Figure 3.1 CoP Sensor (adapted from [107])

I. Operating Principle

The CoP sensor relies on the middle layer of pressure conductive rubber to effect the principle piezoresistive transduction. When a normal pressure distribution or impact force impinges on the top layer of the sensor, the resulting deformation of the middle pressure conductive rubber layer results in a reduction of resistance within it which in turn induces greater current flow in the top-bottom direction. This increase in current flow between top and bottom layers varies the two voltage differences between electrodes S_1 and S_3 as well as S_2 and S_4 on the top and bottom conductive layers respectively. The two resulting values could be utilized and calibrated to ascertain the exact contact location of the normal impact force or center position of the normal pressure distribution as well as determine the total current flow between the top and bottom layers which is proportional to the total impinging force. Figure 3.2 below shows the schematic view of the CoP sensor's operating principle.

Figure 3.2 Schematic view of CoP Sensor

The contact location and total force calculations are described by equations [3.1] - [3.4] below:

$$I_x = a \left(\frac{\lambda}{R_0} + \frac{2}{r} \right) ([v_a]_{S_1} + [v_a]_{S_3}) \quad [3.1]$$

$$I_{yx} = a \left(\frac{1}{R_0} + \frac{2\lambda}{r} \right) ([v_b]_{S_2} + [v_b]_{S_4}) \quad [3.2]$$

$$I = \frac{2V_0 - [v_a]_{S_1} - [v_a]_{S_3}}{R_0} = \frac{2V_0 - [v_b]_{S_2} - [v_b]_{S_4}}{R_0} = k_0 F_n \quad [3.3]$$

$$x_0 = \frac{I_x}{I}, y_0 = \frac{I_y}{I} \quad [3.4]$$

where V_0 is the applied voltage through resistors R_0 , $[v_a]_{S_1}$ and $[v_a]_{S_3}$ are the voltages of electrodes S_1 and S_3 on the top layer a (i.e. boundary conditions for voltage at electrodes S_1 and S_2), $[v_b]_{S_2}$ and $[v_b]_{S_4}$ are the voltages of electrodes S_2 and S_4 on the bottom layer b (i.e. boundary conditions for voltage at electrodes S_2 and S_4), r is the resistance of the conducting film in layers a & b, a is the half-length of y-direction side while λa is the known half-length of the x-direction side of the sensor surface constant, I_x and I_y are first moments of current flowing from top to bottom layers of the sensor through the pressure conductive material in the x and y directions, x_0 and y_0 are the x and y -coordinates of the impact location/center of normal pressure distribution with reference to the center of the tactile sensor, k_0 and F_n are a known constant and total normal force respectively (see Figure 3.1).

II. Performance

In preparing the CoP sensor to detect the ZMP on a single foot of a biped robot, two tests were conducted by Shimojo et al. [107] to gauge the performance of the sensor in terms of time response and positional accuracy. The first test involved utilizing an impulse hammer to generate a consistent impact force with 60N amplitude and an approximate rise time of 1.3ms which resulted in an observed response time of approximately 1ms. The second test was designed to obtain the maximum position error using a device to apply a constant 9.81N normal force on top of an aluminum plate with 6mm-diameter hemispherical structures arranged in a 6 by 6 matrix. In applying the force in 2mm intervals diagonally across the sensor, the maximum error obtained in the x and y directions were approximately 4.6% and 6.5% respectively.

Slip Sensor

The development of the slip sensor grew out of an initial study on the reaction of pressure conductive rubber to slip events conducted by Teshigawara et al. [49] to

determine the principle of transduction of the CoP sensor when used for slip detection [110]. Although the utilization of the CoP sensor was ultimately abandoned due to its inability to differentiate between the normal grip force impact and underlying slip events [48], the Slip sensor has proven to be more successful at slip sensing with the formulation of a compatible information processing method utilizing discrete wave transformation (DWT) to determine the time-stamp for the unique frequency content of its output signal [112]. Structurally, the sensor is composed of two primary layers: i) a pressure conductive rubber top layer and ii) an electrode layer consisting of two electrode traces in a spiral configuration (see Figure 3.3). An early prototype of the Slip Sensor developed by Teshigawara et al. [113] had an area of 6mm by 6mm and a thickness profile of 0.5mm although the authors theorized that the minimum size could go down to as low as 3mm by 3mm. The sensor is connected to a DC power supply providing it with 5V connected through a $1k\Omega$ resistor. It was proven in [48] that the resulting high frequency content of the fluctuation within the voltage difference measured between the pair of electrodes (i.e. v_p in Figure 3.3B) prior to overall slip could be analyzed to ascertain the presence of an imminent or localized slip event of the object surface in contact with the sensor. The following sections describe the operating principle of the Slip sensor and its performance.

A. Structure of Slip Sensor

B. Electrode configuration

Figure 3.3 A. Structure of Slip Sensor and B. Electrode configuration (adapted from [112 & 48 respectively])

I. Operating Principle

Similar to the CoP sensor, the Slip sensor relies on pressure conductive rubber at the top layer to effect the principle piezoresistive transduction. As described in the

section above, deformation of the pressure conductive rubber layer due to the initial impinging normal pressure distribution or impact force will result in an initial reduction of resistance between the two electrodes at the bottom layer and a corresponding decrease in v_p . In an experiment conducted in [114] involving an initial normal force loading on the sensor as seen in Figure 3.4 (circled in red), introduction of tangential load force F_x at the 0.05s mark up to the point of actual object slip will result in an *increased* resistance and corresponding increase in the voltage difference between the electrodes compared to the starting voltage resulting from the initial normal force load alone. At 0.4s, the magnitude of F_x had resulted in the object to slip (i.e. at 0.4s) beyond which the magnitude of the force remains constant while the object continues to move (as evident from the laser displacement sensor output). Focusing back on the measured voltage difference prior to slip, the complicated signal measured (circled in blue in Figure 3.4) was ascertained to have consisted of a uniquely high frequency measuring in at several to tens of kilohertz [48]. Through digital processing utilizing DWT to ascertain the power of the voltage difference signal at unique frequencies with respect to the specific times they occur within, a distinct threshold level could be prescribed for the resulting power signal obtained with which the time of initial slip (i.e. localized slip) *prior to* the actual overall slip could be ascertained. Figure 3.5 shows the schematics of the Slip sensor used for slip detection.

Figure 3.4 Change in voltage difference between electrodes with tangential load towards slip (adapted from [114])

Figure 3.5 Schematic view of Slip Sensor

Comment on the source of transduction of the primary pressure conductive rubber

Teshigawara et al. had theorized in [110] and [114] that the piezoresistive behavior of the pressure conductive rubber layer of the Slip sensor lies within the change in bulk resistance instead of contact resistance (i.e. contact between the rubber and the electrodes) based on their results obtained from experiments involving the introduction of normal followed by tangential impinging forces on the surface of an ad-hoc sensor created by placing a pressure conductive rubber in between two electrodes. They hypothesized that with impinging normal force, the uniformly distributed but separated conducting particles within the pressure conductive rubber would form an increasing number of conducting routes between the electrodes due to the subsurface normal deformation experienced resulting in a reduced resistance. With tangential loading force, shear deformation within the pressure conductive rubber would result in the breaking up of the previously-formed conducting routes leading to a corresponding increase in the resistance as mentioned above. However, this hypothesis contradicts results obtained from two other studies [85 & 115] which concluded that the piezoresistive characteristic of pressure conductive rubber is derived mainly from changes in the contact resistance between the rubber and the electrodes. In both of the aforementioned studies, the conclusion was arrived at when almost no piezoresistive behavior of the pressure conductive rubber was

observed under normal impinging force when the electrodes were individually shorted to the pressure conductive rubber surface as opposed to when they were not. This author therefore states that the real source of the piezoresistive behavior within the Slip sensor could be ascertained by performing an experiment where the electrodes are shorted through the use of conductive adhesive. The importance of the results obtained lies in its potential ability to ultimately determine the appropriate theoretical model to characterize the piezoresistive behavior of the slip sensor to be utilized in the proposed tactile feedback system.

III. Performance

Teshigawara et al. performed a series of test [113 & 114] to gauge the performance of the sensor in terms of time response and positional accuracy. The first test which involved effecting shear deformation of differing magnitudes to ascertain the sensitivity of the sensor showed that the sensor was able to respond to a minimum deformation of 0.01mm. The second test involved effecting the shear deformation at different rates. The results showed a trend in which the sensor responded with increasing voltage difference for increasing deformation rates beginning with an initial steep gradient that becomes more gradual at higher rates as seen in Figure 3.6. Finishing up with third test which aims to quantify the effect of different initial normal force on shear force sensing, Teshigawara et al. [114] concluded that the slip sensor was dependent on the initial normal distortion (i.e. caused by initial normal force) and shear deformation rate.

Figure 3.6 Graph of shear deformation rate against voltage change for Slip Sensor (adapted from [114])

Integration of Tactile Sensor Component

The integration of CoP sensor and Slip sensor has been successfully conducted and tested for an autonomous multi-fingered hand system robot in [48] as shown in Figure 3.7. The result obtained showed that the robot equipped with the integrated sensor was able to automatically adapt to increase in weight of the grasped object automatically without any human intervention [48]. The current work assumes that the tactile sensor is to be used in conjunction with a Cadiere grasper which affords a large contact area measuring 14mm by 5mm [102]. Therefore to enable mounting onto the jaw of the surgical instrument, both the CoP and Slip sensor will be constructed out of a basic commercially available A201 FlexiForce piezoresistive force sensor (refer to Appendix A) which measures in at 203 μ m thickness, a width of 14mm and an effective sensing area of 9.53mm as seen in Figure 3.8. It is able to measure from 0 to 110N and has a response time of under 5 μ s. In [102], King had reported successfully reducing the width to 5mm through a dicing process and integrating it together with an in-house constructed electrode prior to mounting the sensor onto the Cardiere grasper's contacting jaw. The following section describes further the proposed approach for the construction of an integrated CoP and Slip sensor using the FlexiForce piezoresistive force sensor.

Figure 3.7 Integration of CoP sensor with Slip sensor on a single finger of a multi-fingered robot (adapted from [48])

Figure 3.8 Structure of FlexiForce force sensor

Construction approach

The proposed approach to fabricating the tactile sensor component consisting of both the CoP sensor for grip force measurement and Slip sensor for slip detection involves directly substituting the pressure conductive rubber with the pressure sensitive ink (made of polyimide-based, carbon-filled paste from Electro Science Laboratories (ESLRS15114)) similar to what was reported in King [102]. As shown in Figure 3.8, a single FlexiForce sensor consists of two symmetrical parts each composed of an insulator flexible substrate, a conductive silver layer and the pressure sensitive ink glued together with adhesive. The approach involved the following steps:

1. Separate the two symmetrical parts.
2. The width of each part was trimmed down from 14mm to leave behind a 5mm-wide pressure sensitive area through dicing process.
3. Microfabricate the circuitry for the unique electrodes of both CoP and Slip sensors (i.e. the orthogonal edge pair and pair of spiral electrodes respectively) with necessary interconnects made from gold with chromium layer deposition on a 127 μ m thick polyimide film through sputtering or E-

beam evaporation process. The polyimide film will first be adhered onto a standard 4 inch wafer while the specific shape and structure of the traces will be constructed through a dry-film development/lift-off process.

4. Adhere the individual components (i.e. the FlexiForce sensor segment and circuitry layers together) to make up individually the CoP sensor and the Slip sensor.
5. Elastomer-based protective layer to be placed on surface of the sensors.

Figures 3.9 and 3.10 show the layers for the CoP and Slip sensors respectively:

Figure 3.9 Layers of CoP Sensor from modified FlexiForce force sensor

Figure 3.10 Layers of Slip Sensor from modified FlexiForce force sensor

Summary of Section

This section described the tactile sensor for the planned tactile feedback system to restore the necessary tactile feedback during tissue grasp or manipulation. An integration of the CoP and Slip sensors was proposed in order to achieve the two tasks with each of the two sensors' principle of transduction described in detail. A viable approach was then described to construct the two types of sensors from commercially available A201 FlexiForce pressure sensitive sensors through microfabrication for suitable mounting onto a proposed Cardiere grasper. The following section will describe the tactile display component.

3.1.2 Tactile Display

The second essential requirement of the proposed tactile feedback system for effective grasping and manipulation of tissue subsequent to measuring the grip force and detecting slip on the is the accurate replication of the normal grip force and the necessary tactile feedback during slip for facilitating automatic grip response. To fulfill these two requirements, the tactile display would consist of two elements which parallels the earlier described tactile sensor component: i) one to replicate grip force measured through the CoP sensor and ii) one to replicate the controlled growth of the slip region when localized slip is detected by the Slip sensor. The grip force display would consist of a linear motor actuated system providing normal force display while the slip display features a pneumatically actuated balloon-based tactor. Figure 3.11B conceptualizes the application of both elements of the tactile display component integrated onto one of the EndoWrist manipulator located on the master console of the da Vinci Robotic Surgical System. The following subsections will describe the grip and slip display elements of the tactile display component in greater detail.

A. Original da Vinci Master Control

B. Master Control with Slip & Force displays

Figure 3.11 A. The EndoWrist manipulator of the da Vinci RMIS. B. Conceptualization of the Slip & Force display elements

Grip force display

The task of the grip force display is to replicate the normal force impinging on the contact surface of the surgical instrument (e.g. Cardiere grasper) during grasping or manipulation of tissue onto the glabrous skin of the operating surgeon's index fingertip and thumb. Figure 3.12 and 3.13 below shows the control scheme

and conceptual design of the display integrated with the EndoWrist manipulator respectively. As seen in the in Figure 3.13, the linear motor properly secured within the bottom compartment of the control generates an up-down stroke which is converted by the two links into an open-close motion of the EndoWrist manipulator that in turn releases or compresses the spring secured between the manipulator's grip flap. The compression and release of the spring converts the displacement of the linear actuator's stroke length into force which is then transferred onto the glabrous skin of the surgeon's skin through contact with the grip-control. The function of the linear actuator is to relieve the force exerted by the spring through a downward stroke during the initial stage of a grasp when the user squeezes the grip to initiate jaw compression up to the point before contact with tissue as well as to release the spring through an upward stroke allowing for grip force to be replicated onto the fingertips once contact with tissue has been made. As stated in Section 2.2.1, the display is required to replicate a force range of between 0 to 5N and operate at a frequency of 5-10Hz. Control is achieved through a microprocessor which outputs PWM signal with varying duty cycle based on the sensor input measurement as seen in Figure 3.12.

Figure 3.12 Control scheme of grip display

Figure 3.13 Grip display on the EndoWrist manipulator

Slip display

The slip display is tasked to restore the characteristic tactile feedback during slip necessary for evoking the automatic grip response. The Slip display features a single balloon-based tactor which could cover the entire area of the glabrous skin measuring 1-2cm² on the index fingertip and thumb when fully expanded. The purpose of the tactor is to be able to replicate a form of skin deformation similar to the characteristic expansion and contraction of the slip region of the contact surface as described in Section 1.3.1. To reiterate, expansion of peripheral slip region towards the high pressure center of the contact surface resulting from failure to adapt to lower friction or introduction of tangential load forces would result in a higher number of localized slip which would evoke a large number of FAI tactile afferents at a high rate and thus elicit the automatic grip response. Thus while initial contact during grasping of tissue signaled by the CoP sensor would result in a full inflation of the balloon-based tactor, it is envisaged that the contracting tactor would replicate the skin deformation described earlier when localized slip is detected by the slip sensor (refer to Figure 3.14). By managing the rate of contraction based on the strength of the signal measured from the Slip sensor, the

strength of the response from the FAI tactile afferents could be increased or decreased and, in consequence, the automatic grip response as well.

Figure 3.14 Principle of operation for proposed slip display

The expansion and contraction of the balloon tactor of the slip display is effected by a pneumatic system similar to the one described by Goethals [85] and King [102]. The primary approach involves the utilization of an off-site pressure regulator, a 3/2 way valve and a separate air bleed downstream pressure regulator to control the air flow into and out of the tactor thus allowing for a light-weight and flexible design for the onsite tactor interface as seen in Figure 3.11B. Figure 3.15 below describes the control schematic view of the slip display. As the pressure regulator is typically controlled by an analog DC voltage signal, the PWM signal output generated by the control unit microprocessor based on the input of the Slip sensor signal will first undergo a digital signal processing unit with an RC low-pass filter to generate the required DC voltage input signal as shown in Figure 3.15. In order to attain a light-weight and flexible onsite tactor interface, King [102] constructed the balloon-based tactor from silicone on top of a polydimethylsiloxane (PDMS) substrate. The PDM substrate substrate was cured within an aluminum mould allowing the creation of a central channel for air in and out flow while the silicone based tactor was constructed through spin coating process on a standard 4-inch silicon wafer to attain a uniform thickness. Once the substrate is set, it is

placed on top of the wafer allowing the silicone to cure and adhere onto the substrate.

Figure 3.15 Control schematic view of slip display

3.1.3 Integrating Control Component

The function of the tactile feedback system first mentioned at the end of Chapter 1 could be described as seamless integrating of the individual tactile sensor and display components. The overall scheme, as seen in Figure 3.16 below, seeks to describe the flow of information from the moment of initial measurement of the grip force and detection of slip at the instrument/grasped tissue interface through the tactile sensor to the control unit which processes the raw data and executes the needed control algorithm before sending out the necessary signal input to the tactile display component for replication of the necessary tactile feedback onto the glabrous skin of the surgeon's fingertips. There are therefore two events in which the framework and tactile feedback system takes account for during the task of grasping or manipulating tissue: i) the increasing or decreasing of grip force and ii) the occurrence of localized slip. As the operating details of each of the sensor and display components (e.g. CoP sensor, slip display) have been described in the earlier sections, the following subsections will focus on the synthesis of these two events in its entirety as well as the control aspects required.

Figure 3.16 Overall scheme view of the tactile feedback system

Replication of grip force

The replication of grip force focuses on the operation of the CoP sensor, Force and Slip displays as seen in Figure 3.16. When contact is made between tissue and jaw of the surgical instrument, the elastomer-based surface of the customized CoP sensor element of the tactile sensor component mounted on the jaw will transduce the impinging normal force and deform the pressure sensitive ink layer (refer to Figure 3.9) resulting in a change of resistance and corresponding voltage output signal 1 which reflects the total normal force engaging the sensor. The analog voltage output signal 1 will then be relayed through the readout circuitry before being converted into a digital signal through an ADC component of the control unit for input into the microprocessor unit of the control unit component. The control algorithm within the microprocessor will then determine the appropriate displacement required for the linear actuator of the grip force display to replicate the measured normal force onto the glabrous skin of the surgeon's fingertips based on

the voltage signal 1 input before yielding the required duty cycle for the PWM signal input to the control servo or driver. In addition, the control algorithm will also result in an output for the downstream pressure regulator for full expansion of the slip display's balloon-based tactor (a more detailed explanation of the function of the slip display will be described in the next subsection). The control algorithm for the grip force display will depend on both the stiffness as well as the compression/extension length of the spring element of the display (refer to Figure 3.13) resulting from the up/down stroke of the linear actuator in order to calibrate the output force.

Replication of tactile feedback associated with slip

For active slip display of the proposed tactile feedback system, the two main components are the Slip sensor and display. Slip occurs subsequent to the initial contact typically during preloading and loading phases when there is a need to adapt to the friction when grasping tissue as well as during later periods when external loads tangential to the contact surface are introduced i.e. during collision with other obstructing tissue or when extension limit of fibrous attachments between tissue and body is reached. In both cases, the localized slips taking place at the interface of the contacting jaw and tissue will result in the high frequency fluctuation of the output voltage signal 2 as described earlier in Section 3.1.1. Similar to the case of the CoP sensor, voltage output signal 2 will then relayed to an ADC component and be converted into a digital signal before input into a computer within which the discrete wave transformation will be performed. The subsequent power output will then be relayed to the microprocessor and the control algorithm will determine whether the magnitude of the signal is above the threshold of prescribed for slip detection. Once determined to fulfill the threshold, the signal required for the downstream pressure regulator will then be determined based on the required contraction rate of the balloon tactor depending on the magnitude of the DWT power output signal. The contraction of the balloon-based tactor at a controlled rate will replicate the similar growth rate of the slip region characteristic of localized slip. In short, a controlled elicitation of the FAI tactile afferents and corresponding automatic grip response could be achieved. Once the appropriate values have been calculated through the control algorithm, the microprocessor will then generate the

required output signals to: i) switch the 3/2 valve to connect to the downstream *contraction* pressure regulator and disconnect with the upstream *expansion* pressure regulator, ii) output the appropriate duty cycle for the PWM output signal for the downstream pressure regulator. As described earlier in Section 3.1.3, the PWM output signal will be converted to an appropriate DC analog voltage signal for input into the downstream pressure regulator.

3.1.4 Summary of Section

This section describes the flow of information within the tactile feedback system with the tactile sensor and display components working in tandem for the purpose of grip force and slip-associated tactile feedback replication which plays a primary enabling role in the solution proposed. In summary, the normal grip force will be monitored element and measured with the voltage output of the CoP sensor element throughout the task of grasping or manipulation of tissue and replicated through appropriate linear actuation of the grip display and full expansion of slip display's balloon-based tactor from the moment of initial contact. At the same time, slip detection through high frequency fluctuations output of the slip sensor element beyond the threshold magnitude within this period will result in a controlled contraction of the balloon-based tactor of the slip display thereby restoring the necessary slip-associated tactile feedback and evoking a controlled automatic grip force response to prevent slip. The following section will describe the proposed framework architecture which governs the function of the tactile feedback solution in order to effect the solution.

3.2 Tactile Feedback System Framework

In the proposed solution to the problem of impeded natural grasping within RMIS, the implementation of the aforementioned tactile feedback system is to be governed under a novel framework formulated to effect sufficient grasping transparency. Due to the severe demands on time to properly invoke the desired responses from tactile afferents necessary for the restoration of natural grasping [37 & 38], the framework proposed is composed of a novel architecture that complements direct bilateral control through shared control at both the local and remote sites. While primarily poised as a viable alternative to the out and out

improving of transparency for better telepresence [105], the use of shared control in the framework is specifically aimed to assist in effecting sufficient tactile feedback to invoke operator's natural response at the local site while enabling prompt autonomous response at the remote end to ensure sufficient grip force before overall slip occurs. The combined actions provide access to tactile sensations associated with the incipient slip at the local site which is synchronized with the autonomous response at the remote site. This affords a level of transparency sufficient for natural grasping. The following sections will describe the framework further beginning with its principle of operation.

3.2.1 Principle of Approach

Provision of haptic feedback towards transparency represents a crucial element for the promotion of improved general task performance as well as efficient task completion times within teleoperation [105]. Within the broader application of human-automation interaction, design guidelines stated by Abbink et. al [116] called for the delivery of continuous feedback on automation boundaries and functionality to the human operator. With regards to grasping in particular, Griffin et. al [117] explicitly highlighted the need to provide a sense of presence for the operator due to innate relaxation of the human grasp in the absence of tactile sensation. Consequently, in affording unimpeded natural grasping within telerobotic RMIS by restoring innate responses to changes in friction as well as unexpected loading force, the pursuit of grasping transparency through timely provision of incipient slip-related tactile feedback at the local site in sync with incipient slip detection at the remote site is critical.

The principal approach undertaken to provide accurate and on time presentation of the necessary incipient-slip related tactile feedback at the local site in synchronization with actual incipient slip detection at the remote site will be fulfilled through the shared control architecture. A hybrid shared control architecture consisting of the input-mixing shared control [106] together with the haptic shared control [116] was utilized. While the former control method allows for both operator and robot to give commands simultaneously, the latter provides the robot with the authority to supersede given commands when necessary. The motivation behind blend shared control is that it allows for prompt autonomous

response at the remote site, the intention behind the haptic shared control implemented within the framework is not to directly invoke the operator's response but rather to preserve and enhance the tactile feedback communicated to the local site. The following section will describe the implementation of the framework in detail.

3.2.2 Implementation of Framework

Figure 3.17 Tactile feedback system framework

The proposed framework, as seen in Figure 3.17, is to be operational only post-contact once object has been grasped by the robot. Force feedback F_{FS} is fed back into the Master display device (refer to Section 3.1.2) and will be displayed continuously by the grip force element of the grip force display. The force feedback will be utilized to invoke the initial grip force required by invoking natural response (i.e. how hard or soft from the operator at the local site through the force display element of the tactile display refer to Section 3.1.2, Grip Force Display). Sufficiency in grasping force will signal a shift in control to the autonomous

element of the input-mixing shared control which will maintain an optimal safe region for grasp force based on incipient slip detection. When subsequent incipient slip is detected through the tactile sensor due to perturbing forces, the controller will allow autonomous response at the remote slave end while providing input to the Master slip display for continuous tactile feedback to the operator. The input into the Master would depend on the proposed predictive model which will be described further in Chapter 5. At the same time input to the master, F_F , will be cut off and will only resume when there is a reduction which signifies intention to release object during which control will revert back from the robot to the operator.

3.3 Chapter Summarization

This Chapter has described the proposed tactile feedback system as well as a framework to implement it within the telerobotic RMIS setup. The tactile feedback system proposed consists of tactile sensor to detect incipient slip and load as well as a tactile display to communicate the load force and incipient slip. A hybrid input-mixing and haptic shared control architecture is proposed for the framework to allow for prompt autonomous support in the event of a slip at the remote slave end as well as provide for sufficient tactile feedback to the operator at the local site without lag through the use of predictive model. The next section describes the incipient slip sensing element as well as the experimental setup developed to test the model for incipient slippage.

Chapter 4

Detection of Localized and Incipient Slip

The focus of this chapter is on the method developed for detecting incipient slip, a key element for effecting the proposed tactile feedback system. To recount, it had been established that inherent loss of incipient slip-related tactile sensations in current RMIS procedures presents a barrier to natural grasping before the current state of tactile feedback system development was postulated to be wanting with regards to this area of application in Chapter 1. The latter was then shown to be conclusive with the absence of a ready tactile feedback system capable of timely detection of incipient slip and replication of appropriate tactile sensation having been surmised from the subsequent review of relevant literature pertinent to tactile feedback systems conducted in Chapter 2. In response to the gap in technology therefore, a design of an incipient slippage tactile feedback system capable of detecting incipient slip and replicating the relevant tactile sensations together with a framework which leverage on shared control to achieve sufficient transparency for grasping were proposed and formulated in Chapter 3. Consequently, it was made apparent that accurate detection of incipient slip during grasping is a critical element thus paving the way for the material to be discoursed in the current chapter.

The current chapter describes the principle and methodology behind the proposed detection of incipient slip approach and the experimental setup established to assess the efficiency of utilizing a piezoresistive sensor for the purpose. Section 4.1 describes the main principle of detection providing a short background and supporting literature behind it. Section 4.2 describes the sensing element and the motivation behind the design factors. Section 4.3 describes the experimental setup as well as the tests conducted to validate the method described. Section 4.4 summarizes and concludes with the main points of the Chapter.

4.1 Principle of Approach and Background

Cognizance of incipient/localized/partial slip is critical for the stable manipulation of objects in humans [42]. As stated earlier in Section 1.3, incipient slip comprises the first of two sequential types of slip that would occur on the contact surface in the course of a failing grasp. Incipient slip is described as partial segmented delaminations of the two contacting surfaces due to uneven distribution

of forces that occur without catastrophic compromise to the overall grasp integrity. A precursor to total slip, the early timing of tactile sensations arising from incipient slip as accrued through numerous tactile afferents within the glabrous skin enables the biological analogue of a closed loop control of grasp force that could quickly adapt to different surfaces [37] as well as unexpected exertions of potentially destabilizing forces [38]. In contrast, as evident in the work conducted by Johansson and Westling [37, 38, 39 & 40], fingers that were anesthetized prohibiting access to tactile feedback experienced significant degradation in terms of delayed and/or deficient grasp force response. Consequently, the loss of tactile feedback intrinsic to the current RMIS procedures strongly portends a need for effective means of detecting incipient slip to restore natural grasping.

Within the field of robotics, detection of incipient slip is postulated to play a critical role towards ensuring dexterity, stability and flexibility in robotic hands [48 & 119] with detection of incipient slip through measurement of vibration being a close emulation of natural human detection that comprises one of the four classes of viable slip detection methods [120]. The sensor constructed by Tremblay and Cutkosky [121] was centered on a hemi-cylindrical foam core with a silicone rubber skin. The micro-vibration that was generated during localized individual slips of purpose-built nib structures on the skin was detected through four strips of piezoelectric film laid across the sensor embedded within the rubber skin. The origin of the design and others similar to it [2, 122 & 123] was derived from an earlier sensor constructed by Howe et al. [124] consisting of a similarly hemi-cylindrical hard inner plastic core with an external textured silicone rubber surface to simulate skin. Vibration at onset of incipient slip was achieved through a ‘catch and snap back’ action on the external skin which produces intense localized accelerations detected by accelerometers without the need for any overt external structures. In a design by Teshigawara et al. [48], the utilization of pressure conductive rubber (PCR) as both compliant surface and transducer mounted onto a robotic finger was leveraged to achieve a more compact and easily-adaptable design. True to the two preceding design, vibration that was induced at onset of incipient slip on the surface of the PCR was detected in-situ. In addition, instead of the direct measurement of vibration per se, a high-frequency component threshold of the resulting force was defined and detected to signal onset of incipient slip.

Consequently from the above descriptions, the three different implementations of the same detection approach could be seen to share the following common features which closely emulate three key characteristics in natural human detection:

- i) Concavity/curvature of compliant surface, with or without apparent external structures, to facilitate an ordered distribution of normal force from weakest at the periphery to strongest at the centre similar to the contact surface of a grasping fingertip,
- ii) generation of micro-vibrations at the beginning of slip on the surface similar to partial sliding of the ridged skin surface on object, and
- iii) detection of said vibration through transducer analogous to the FAI afferents embedded beneath the skin of the fingertip.

The idea behind this, as seen in Figure 4.1, is that resulting distribution of force due to normal force caused by the concave contact surface will result in partial slips occurring at the periphery in the event of sufficient tangential force which would generate micro-vibrations that could be detected by a transducer prior to total slip. This concept forms the principle of the approach which was adapted in the current work. The method adopted and the experiment conducted will be described in the following two sections.

Figure 4.1 Conceptualization of incipient slippage at periphery of concave surface

4.2 Design of Incipient Slip Sensing Element

A complete implementation of the incipient slip detection approach described in the prior section comprises the following three main facets: i) inducement of incipient slippage and resulting vibration at onset, ii) transduction of vibration into functional data i.e. voltage, current, iii) signal processing of data into comprehensible metrics of the vibration i.e. frequency, amplitude is shown in Figure 4.2. The design for the basic structure of the sensing element relating to overall shape, surface texture and compliance, will be governed by the first facet. Selection of suitable transducer must be made to comply with conditions stipulated based on the second facet. The final aspect is related to the method undertaken to identify and localize the moment when incipient slip-induced vibration occurs through characterization of the resulting force (refer to Section 4.2.3). The following sub-sections will describe the actual implementation:

Figure 4.2 Implementation of incipient slip detection

4.2.1 Basic Structure of Sensing Element

The fundamental structure of the sensor is driven by the need to facilitate a partition of strong and weak-forced areas within the contact area in order to induce ready incipient slip with the onset vibration resulting from the partial delaminations of the skin surface. Curved and compliant surface emulating the fingertip (see

figure 4.1 and 4.2), as demonstrated in numerous sensor implementations [121, 123 & 124], remains the most direct means of achieving the necessary distribution of forces. In accordance, the sensing element is constructed upon a cylindrical aluminum core measuring at 20 mm axial length and 19 mm diameter. To facilitate a sufficiently compliant surface, the selected FlexiForce A201 sensor (refer to Section 4.2.2) with a total of 208 μm thickness on a flexible Mylar-based substrate was mounted to conform onto the forward-facing section of the cylindrical core with a thin adhesive layer. The piezoresistive-based sensor allows for the transducer element to be directly integrated onto the surface with a designated sensing area measuring in at 9.53 mm in diameter. Electrical connection for input and output signals is achieved through a conductive silver-based adhesive running through the length of the FlexiForce A201 sensor ending at two conducting pins at its tail-end. As shown in Figure 4.3, the cylinder-piezoresistive sensor assembly was mounted onto a FuTek LSB200 load cell (refer to Appendix B) with a range of 0 to 22 N used to measure the tangential load.

Figure 4.3 Basic structure of the sensing element

4.2.2 Selected Transduction Method

In her review of slip sensing and artificial sense of slip, Francomano et al. [120] had stated that vibration could either be measured indirectly through its source or directly based on the strength and frequency. The primary limiting condition for measurement is derived from the need to account for multiple harmonic components, specifically the higher components which may be associated with the moment of incipient slip [48]. Originating from the aforementioned condition, parameters related to the speed of derivation of functional signals must also be accounted for. For the proposed sensing element, a direct means of detection and measurement was selected in the form of the abovementioned FlexiForce A201 piezoresistive sensor (see Figure 4.4). The model selected was able to account for an effective normal force range of 0 to 4.4N. To accommodate for the overall design of the cylindrical aluminum core as well as overall experimental setup (refer to Section 4.3), the longer 197 mm model with a width of 14 mm was selected. The sensor is constructed in a symmetrical layered manner with the electrical input/output component, consisting of silver-based conductive adhesive running from pin to pressure sensitive ink layer mounted on a flexible mylar-based substrate, bounded together by 2 layers of adhesive as seen in Figure 4.4. When current is run between the input and output pins, pressure applied onto the sensing area will result in decrease in resistance from effectively infinite to theoretically 0 Ω . The signal output was amplified through readout circuit shown in Figure 4.5 and the output signal transmitted to a PC via DAQ (refer to Section 4.2.3). The sensor utilized was calibrated and it was determined to have an effective linear range of between 0.65 N to 2.2 N with a sensitivity of 1.67V/ N (see Figure 4.5).

Figure 4.4 FlexiForce A201 piezoresistive sensor

Figure 4.5 Load/Voltage graph and inverting amplifier circuit interface for voltage signal output

4.2.3 Signal Processing

The vibration-based incipient slip sensor design proposed by Teshigawara et al. [111] consisting of a pressure conductive rubber on a scalable spiral electrode eliminated the problem of false slip detection during the initial grip contact with grasped surface. In this method, force measurements through time are analyzed through various tools (i.e. Fast-Fourier Transform (FFT), Continuous Wavelet Transform (CWT) and Discrete Wavelet Transform (DWT)) to determine occurrence of its high-frequency content which typically represent moment of incipient slip. The signal output of the FlexiForce A201 piezoresistive sensor mentioned in prior Section is directed through an NI USB-6259 16-bit DAQ (see Figure 4.6) and analyzed utilizing Discrete Wavelet Transform (DWT) programmed using LabView software (refer to Appendix C). In Figure 4.7, the top graph consists of the normal force (white), displacement (green) and tangential force (red) while the bottom graph shows the resulting DWT of the normal force for the 50 kHz-100 kHz range as a function of time. Tangential force is applied to the object in contact with the sensing element and a significant increase in DWT was shown at 6.6s a full 200 μ s before a significant dip in displacement (i.e. 133 μ m) was measured.

Figure 4.6 National Instrument's NI USB-6259 16-bit data acquisition system (DAQ) with 32 inputs at maximum 1.25 Ms/s

Figure 4.7 Overall Graph: Normal force (white), tangential force (red), displacement (green) and Discrete Wavelet Transformation (DWT) Graph

4.2.4 Summary of Section

In the prior Section, the implementation of sensing element along with the design motivation were described and detailed. A schematic view of the different components of the complete sensing element to be mounted onto the experimental setup is shown below in Figure 4.8. Input voltage signal to the sensing element's FlexiForce A201 piezoresistive sensor is provided through the powered readout circuit while the output voltage signal is then directed to the DAQ to be digitized and streamed to the PC. DWT is performed through LabView software to process the data stream and determine the magnitude and frequency of the vibration harmonic components. Simultaneously, input and output voltage signals of the Futek LSB200 load cell are processed in a similar manner through the Futek CSG110 amplifier. The specifications of the sensing element are summarized in Table 4.1. The next section describes the experimental setup.

Figure 4.8 Complete schematic view of sensing element

Table 4.1 Specifications for sensing element

Size	Height (mm)	Width (mm)	Thickness (mm)
	35	9.53	19
Normal Force	Minimum (N)	Maximum (N)	Sensitivity (V/N)
	0.65	2.2	1.67
Tangential Force	Minimum (N)	Maximum (N)	Sensitivity (V/N)
	-22	22	0.46

4.3 The Experimental Setup

In order to validate the feasibility and performance of the sensing element and other additional studies deemed necessary for the detection of incipient slip in this body of work, an experimental setup is constructed with the primary objective of enabling controlled induced incipient slips on the contact surface between the sensing element and grasped object. In principal, this entails the need to exert different grip and load forces normal and tangential to the contact surface respectively and to be able to monitor both displacement and forces produced in relation to the detection metrics (i.e. the frequency and magnitude of the normal force; refer to Section 4.2). Mini-servomotors were selected as the primary means for actuation while various sensing devices in the form of external load cells and displacement sensors were utilized to measure accurate external forces as well as movement. The front and side views of the complete setup in schematic view and live pictures, as shown in Figures 4.9 and 4.10 respectively, show that the setup primarily comprises two main parts namely: A) Sensing Element Carriage Way (green portion) and B) Object Carriage Way (yellow portion) which as the names suggest provide means of actuation for the sensing element and object respectively. The detailed description of the setup is provided in the following sub-sections beginning with the general experimental design followed by the two components.

4.3.1 Experimental Design and Overall Setup

The design of the experimental setup is based on the experiment steps designed to induce a controlled incipient slip on the contacting surface comprising the sensing element loading area and the exposed gripped object surface. The setup is imbued with a total of two degrees of freedom, one exclusively to exert different grip force normal to the contacting surfaces and the other for the required tangential load force. Actuation of the two forces is achieved through PID position control of two Faulhaber MiniMotors (refer to Appendix D) using Galil DMC-18x2 PCI card (refer to Appendix E) fixed into an Intel Core 2 Duo E6750 cpu-based PC running Windows XP with 3 GB RAM (see Figure 4.8) with Advanced Motion Controls (AMC) Analog DC Drives (refer to Appendix F). Position control of the minimotors are programmed using GalilTools interface (refer to Appendix G). In addition to the designed sensing element which comprises the A201 Flexiforce piezoresistive sensor and the Futek LSB 200 load cell to measure normal grip force

and a tangential load force respectively, the setup is also equipped with a Keyence LK-G402 laser displacement sensor (refer to Appendix H) to measure accurate and precise position of the gripped object. All raw analogue data from individual sensors are fed into an NI USB-6259 DAQ (see Figure 4.8) to be converted into streamable data to the PC. The data are processed in real-time and offline with applications programmed in LabView 2009 (refer to Appendix A). The following describes the principle steps of the general experiment conducted:

1. Initialize positions of sensing element and grip object.
2. Move sensing element from its initialized position until contact is made between its loading surface and object surface.
3. Continue loading the sensing element onto the grip object until desired normal required force is reached as measured through the output of the A201 FlexiForce piezoresistive sensor.
4. Begin increasing tangential loading force until full slippage occurs.
5. Record outputs of Futek load cell (tangential loading force), A201 Flexiforce piezoresistive sensor and Keyence LK-G402 laser displacement sensor through NI USB-6259 DAQ.
6. Perform DWT offhand using application programmed in LabView 2009 in PC.

Movement of sensing element and gripped object are achieved through the Sensing Element Carriage Way and Object Carriage Way which will be described next.

Figure 4.9 Front view of setup

Figure 4.10 Side view of setup

4.3.2 Sensing Element Carriage Way

The Sensing Element Carriage Way, as shown in Figure 4.11 below, is tasked with controlling the movement of the Sensing Element, exertion of the desired normal grip force on the contact surface and measurement of grip force and tangential load. The primary component, Actuator A, comprises a Faulhaber Mini-Motor (model 2224UO24SR with Series 22/6 185:1 Gear and Series IE2-512 encoder) coupled onto a THK LM Guide Actuator Model KR20 to form a ball-screw system with a theoretical count of 378880/mm. An L-plate aluminum carriage is screwed onto onto the THK Guide upon which the sensing element is mounted. The carriage way provides two-direction horizontal actuation starting from the initialized starting position up to contact with the object (see Figure 4.9 and 4.10). The grip force exerted is measured and monitored online with the A201 FlexiForce piezoresistive sensor while the tangential load force to induce slip is measured through the Futek LSB 200 load cell (see Table 4.1). The frequency content of the former is also to be analyzed with DWT programmed in the LabView 2009 application for ascertaining moment of incipient slip.

Figure 4.11 Sensing element carriage way

4.3.3 Object Carriage Way

The Object Carriage Way, as shown in Figure 4.12 below, is tasked with controlling the movement of the gripped object, exertion of the tangential load to induce slip and measuring the displacement of the gripped object. The main component comprises a sliding aluminum rectangular cuboid on bearinged rail connected to a copy of the ball-screw system in the Sensing element Carriage Way component. The displacement of the gripped object is measured with a Keyence LK-G402 Laser Displacement Sensor with a maximum measuring sensitivity of 1V/mm for a range of 2mm.

Figure 4.12 Object carriage way

4.3.4 Summary of Section

In this Section, the principle steps of the planned experiments as well as the experimental setup were described. The steps formulated comprises exertion of different normal grip forces on the contact surface consisting of the sensing element's loading area and the exposed gripped object surface followed by analysis of the different frequency components of the normal force output at moment of incipient slip. To carry out the steps, the setup consisting of two primary

components ‘Sensing Element Carriage Way’ and ‘Object Carriage Way’ each equipped with a complete ball-screw system exerts normal grip and tangential load force to induce slip while measuring both the forces as well as the displacement of the gripped object when slipping. The maximum travel stroke of the ball-screw system is 40 mm. The following section will describe an experimental example to further detail the entire experimental process.

4.4 Sample Experiment

The following section describes an example run of an experiment conducted to detect incipient slip through frequency analysis of force measurement. The objective of the experiment is to ascertain the frequency of the measured force required to detect incipient slip. The purpose of this section is to provide a clear picture of the method and steps taken to perform an experiment using the experimental setup. Similar experiments have been conducted in earlier works by Son et al. [122] utilizing PVDF to detect vibrations which occur during incipient slip and Trembley et al. [121] with specifically dedicated protuberances on the sensor to localize the slippage while amplifying the vibration (refer to the earlier Section 4.1 for more details). As mentioned in Section 4.2.2 Teshigawara [48] designed a sensor consisting of a layer of spiraling electrode covered by a conductive rubber and detected localized leading to incipient slip by monitoring the high frequency voltage variations prior to incipient slip. The following section describes the experimental methods, procedures and results.

4.4.1 Experiment methods

To reiterate, the experimental setup consists of two Faulhaber servomotors for providing normal and tangential forces, a Keyence LK-G402 laser displacement sensor for monitoring vertical movement, a FUTEK LSB200 load cell for measuring tangential force and the A210 FlexiForce to measure the normal contact force and detect incipient slip (refer to Section 4.3 for a more detailed description). A National Instrument NI USB-6259 DAQ is utilized to collect data from all three sensing devices and fed into the PC. Two different applications are programmed in LabView 2009: i) Application A to perform real-time recording and display of normal grip and tangential load forces as well as displacement of object after slip,

and ii) Application B to perform discrete wavelet transformation for obtaining the specific frequency waveform amplitude against time graph (refer to Appendix C).

4.4.2 Experimental Procedures

The following describes a detailed step by step procedure of the experiment conducted. The steps are illustrated in Figure 4.13.

Procedure:

1. Positions of sensing element and gripped object are first initialized (see Figures 4.9 and 4.10).
2. Actuator A on the Sensing Element Carriage Way (Portion A) is initialized and sensing element is moved closer to surface of gripped object at an initially fast speed (5mm/s), slowing down as it gets closer to the surface (equal to or less than 1mm/s).
3. At reduced speed (~ 0.01 mm/s), surface of sensing element is adjusted to be as parallel as possible¹ to surface of gripped object. Once contact is made, the real-time increase in normal grip force is observed in Application A until the desired normal force is reached (0.55, 0.56 and 0.57N) then Actuator A is stopped.
4. Actuator B is then initiated to move gripped object a distance of 2mm vertically downwards to induce a slip. Speed of motor could be varied as desired.
5. Slip sensor output are monitored and collected through NI DAC at sample clock frequency of 100kHz
6. Data obtained from flexiforce slip sensor undergo discrete wavelet transformation and the amplitude against time for waveform at different observed frequencies was plotted against time. Frequencies whose

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¹ Once the 2 surfaces are close enough to create a narrow slit, a light is shone through the slit from below to provide a gauge as to the degree of gap and the level of parallel between the front edge of the sensing element and the gripped object surface. The degree of parallel could be increased by manipulating the sensor carriageway through tightening and loosening screws that control the vertical and horizontal axis. The 2 surfaces are then made to contact through commands to actuator A, maintaining the level of parallel by observing the diminution of the light as well as the change in output of the PCR-based sensor.

amplitudes at certain threshold are ascertained to be associated with incipient slippage are observed.

Figure 4.13 Experiment steps

4.4.3 Results

Fig 4.14 Plot of normal, tangential forces and displacement against time in comparison with amplitude of normal force variation between 50kHz to 100kHz with normal contact force: 0.55N and speed: 2mm/s

Fig 4.15 Plot of normal, tangential forces and displacement against time in comparison with amplitude of normal force variation between 50kHz to 100kHz with normal contact force: 0.56N and speed: 2mm/s

Fig 4.16 Plot of normal, tangential forces and displacement against time in comparison with amplitude of normal force variation between 50kHz to 100kHz with normal contact force: 0.57N and speed: 2mm/s

4.4.4 Discussion

Based on the results shown in Figures 4.14-4.16, the following could be observed:

- i. A distinctly high-amplitude moment was observed for the waveforms derived from the discrete wavelet transformation at frequency 50kHz to 100kHz of the flexiforce sensor outputs for each initial normal force (0.55, 0.56 and 0.57N).
- ii. All high-amplitude moment occurred prior to gross slip for all three plots.
- iii. Average amplitude values of 0.002, 0.0018 and 0.003 were attained for the DWT plots in Figures 4.14, 4.15 and 4.16 respectively. The magnitudes of the different amplitudes were therefore observed to increase with increase in normal force between 0.55N to 0.57N. The anomaly in the results for 0.56N may be due to too small an increase in normal force between the 0.55N and 0.56N to which higher normal forces tested would show.
- iv. At times of 0.06s, 0.0025s and 0.002s after the initiation of tangential load in Figures 4.14, 4.15 and 4.16 respectively, the DWT outputs were observed

to start rising which corresponds to a decrease in response time with increased normal forces.

The results observed show that the flexiforce sensor could be utilized to detect incipient and possibly localized slippage for the range of initial normal contact forces tested. The initial normal force also affected the time large amplitude takes place for the waveform as well as how early or quick the sensor is able to response. A possible explanation for increasing magnitudes corresponding to increasing initial normal contact force could be that the final amplitude rises offset from the initial normal contact force. The increasing DWT output is due to the more intense vibrations which occurs during the period of localized to incipient slippage due to the higher magnitude of the normal force applied during grip. As for earlier response time being observed for the smaller magnitude initial contact force, it could be concluded that the sensor surface are able to move faster with lesser initial contact force thus making possible an earlier response.

4.4.5 Conclusion of results

The results show that it is possible to utilize the flexiforce sensor to induce high frequency output prior to incipient slippage similar to the results obtained by Teshigawara et al. in [48]. However, it should be added that the functional range of initial normal force that could be applied is much more limited then slip sensors with more intricate designs. The main reason for this observation is due to the simplistic electrode design of the flexiforce compared to that designed in [48].

4.5 Chapter Summarization

This Chapter has reviewed the sensing element, the experimental setup and has described a sample experiment. The sensing element, designed to detect vibrations occurring at the point of incipient slippage, consists of a FlexiForce A201 piezoresistive sensor in which the output voltage signal is then directed to the DAQ before being streamed to the PC where DWT is performed to determine the magnitude and frequency of the vibration harmonic components. The experimental setup has two degrees of freedom (i.e. horizontal and vertical) and is actuated with two Faulhaber mini-motors and is equipped with a Laser Displacement Sensor to measure movement of grasped object. The final section shows an example of an experiment conducted in which the high frequency component of the voltage output

coinciding with incipient slippage was successfully identified. The next section describes the model developed to predict incipient slippage.

Chapter 5

Modeling and Predicting Incipient Slip

The proposed framework described in Chapter 3 calls for a predictive element for detecting incipient slippage for enabling the controller (see Figure 3.17) to effectively provide for the appropriate scale of tactile replication through the master interface at the local site based on incipient slippage detection at the remote/slave site. To facilitate quantitative study of the incipient slip detection during grasping, an experimental setup consisting of two actuators for providing perpendicular motions and various sensors for force and displacement measurements has been designed and built as described in Chapter 4. The purpose of this Chapter is to present the proposed predictive model for incipient slippage and to report on the results of the experiments conducted. It will be shown that the general trend described in the model extension is corroborated by the results of the experiment.

This chapter consists of two halves. In the first part, the proposed model will be described starting with the principal approach of utilizing bendable and compressible beams to represent the sliding mass and the proposed modification undertaken to allow for simulation and characterization of transient normal forces and vibrations at moment of impending incipient slippage. The motivations and rationale behind the characteristic aspects of current approaches is then described together with the drawbacks and shortcoming of current model. An extension to the current approach is then proposed to overcome the drawback and provide a resolution to the short coming. In the second portion of the chapter, the results of the experiments conducted and the significant findings will be reported followed by discussion and conclusion.

5.1 Description of Model

The purpose of the model is to account for and quantitatively correlate the observed high-frequency vibrations to incipient or partial slippage on the contact surface between the end effector and grasped object as reported in the previous chapter (refer to Section 4.4) and in many prior research works [48, 49, 100, 108, 111 & 121]. Evidence for the correlation could also be found in the preponderance of vibration during partial slippages during human precision grasping reported by

numerous psychophysical studies that have been conducted [37, 38 & 43]. The model we proposed in this work constitutes an extension to the work initiated by Ho [125] extend to allow for the quantitative description of the characteristic vibration. The following section will describe the primary elements of the abovementioned model, its rationale and possible shortcomings and drawbacks. Our proposed extension is then described along with its rationale delineated.

5.1.1 Two Dimensional Beam Bundle Model (2DBBM)

Figure 5.1 Modeling of soft deformable fingertip through portioning into compressible and bendable virtual beams

The objective of the 2DBBM is to quantitatively describe transient events occurring during the pre-slide period prior to gross slip. Towards that end, a soft deformable fingertip sliding on a hard frictional surface was chosen as the modeled object. To facilitate the objective, the deformable fingertip mass was partitioned into numerous virtual beams running vertically from the equatorial top region of the fingertip onto the sliding surface as seen in Figure 5.1A. Consequently, the monolithic fingertip surface could be divided into segmented surfaces whereby each movement could be individually quantified, serving as an analogue to partial slippage. As a means of validation, the evolution of frictional force and velocity contrasted with that of frictional force were shown to be qualitatively comparable with that of empirical values obtained as shown in Figure 5.2. A single metric, a Localized Displacement Phenomenon (LDP) defined as the displacement traversed

by the last virtual beam to move during the pre-slip phase, was proposed as the characteristic measure for determining when incipient slippage occurs. The features of the virtual beam, which stands as the mainstay of the model, will be described in detail in the next subsection. This is followed by a step by step account of the modeling process for pre-slip phase consisting of the initiating contact between fingertip and surface up to slippage of the last contact point.

Figure 5.2 A. Results from model, B. Empirical results (Adapted from Ho [125])

Virtual Beam

The primary nature of the virtual beam, as seen in Figure 5.1, is defined as compressible and bendable through which the monolithic normal/grip and tangential/loading forces are channeled through. The structure of the beam is of varying height based on its location along the x-axis (see Figure 5.1) dependent on the curved hemispherical nature of the fingertip surface, with standardized width p and thickness q for all beams. The contact surface is assumed to be embodied by the centre of the beam therefore reducing it to point representation. Each point is imbued with mass m and undergoes Coulomb frictional force as well as interactional forces with neighboring points. Interaction between neighbouring points is assumed to take the form of the Voigt model as shown in Figure 5.1. The stiffness k is taken to represent the interaction between beams as well as the

elasticity of the contact point while the damping coefficient Δd is taken to represent the viscosity of the contact surface. The magnitude of LDP is taken to be the displacement u_0 of the contact point 0 during pre-slide while experiencing mass movement $d(t)$ in the sliding direction. In summary, the forces that are modeled for each beam i are listed as: i) normal force F_i^n due to downward compression of fingertip, ii) bending force F_i^b caused by the lag in motion of the fingertip surface to its equatorial region, iii) friction force F_i^{fr} resulting from the contact between fingertip and the sliding surface, iv) interaction with prior beam F_{i-1}^s and v) interaction with proceeding beam F_i^s (see Figure 5.3). The force equation for each beam i is as follows:

$$F_i^b + F_i^s - F_{i-1}^s - F_i^{fr} = \Gamma_i \quad [5.1]$$

where Γ_i is dependent on the state of the sliding fingertip (i.e. pre-slide, gross slip or change of sliding direction).

Figure 5.3 Forces acting on virtual beam (Adapted from Ho [125])

The formulas for each force are as follows:

Normal force:

$$F_i^n = E \frac{\pi p q}{x \tan \alpha + \sqrt{r^2 - x^2}} \left(d_n - (r - \sqrt{r^2 - x^2}) \right) \quad [5.2]$$

where E - Modulus of Elasticity, d_n - downward displacement of fingertip, r - radius of fingertip, x - x-coordinate/displacement from center of fingertip, α - angle of tilt of fingertip.

Bending force:

$$F_i^b = \Delta b_i s_i(t) = \Delta b_i (d(t) - u_i) \quad [5.3]$$

where u_i is the generalized displacement of an individual beam's contact point, Δb_i bending constant $\Delta b_i = \frac{3EI}{l_i^3} = \frac{Eqp^3}{4l_i^3}$ where l_i is the length of the particular beam.

Friction force:

$$F_i^{fr} = F_i^n \mu \quad [5.4]$$

where μ is the static coefficient of friction.

Force from prior and proceeding beams:

$$F_i^s = k(u_{i+1} - u_i) + \Delta d(\dot{u}_{i+1} - \dot{u}_i) \quad [5.5]$$

$$F_{i-1}^s = k(u_i - u_{i-1}) + \Delta d(\dot{u}_i - \dot{u}_{i-1}) \quad [5.6]$$

where $k = \frac{Es_0}{l_0} = \frac{E\pi d_{r0}^2}{l_0}$ is the spring constant of the Voigt model and d_{r0} is the radius of the spring, $\Delta d = 2\zeta\sqrt{k\Delta m}$ is the damping constant of the model where Δm - mass at contact point and ζ the damping ratio. By putting equations

Modeling of Pre-slip

The modeling of the pre-slip stage consists of the following steps:

1. Initial downward displacement of the entire fingertip to the point of contact defined by the distance d_n (see Figure 5.1). The amount of compression experienced by an individual beam would therefore depend on the position of the beam (i.e. beam 0 at the center will compress the maximum distance d_n while beams away from the center will experience a decreasing displacement). The normal force induced on each beam is calculated as in [5.2].
2. The fingertip contacting the surface is then moved a distance of $d(t)$ function of time in the sliding direction (see Figure 5.3). On sliding, each beam will be deformed during the period in which the contacting point is resisted by the static friction on the surface inducing a bending force defined in [5.3]. At this stage prior to localized slip, the characteristic force equation is

defined as

$$F_i^{fr} = \Delta b_i d(t) + (k(u_{i+1} + u_{i-1}) + \Delta d(\dot{u}_{i+1} + \dot{u}_{i-1})) \text{ i.e. } \Gamma_i = 0 \quad [5.7]$$

3. Once the static friction has been overcome, the contacting point will move a displacement u_i with a velocity of $\dot{u}_i$ while $\Gamma_i = \Delta m \ddot{u}$. The characteristic force is equation is then defined as

$$\Delta m \ddot{u} = \Delta b_i (d(t) - u_i) + (k(u_{i+1} + u_{i-1} - 2u_i) + \Delta d(\dot{u}_{i+1} + \dot{u}_{i-1} - 2\dot{u}_i)) - F_i^{fr} \quad [5.8]$$

4. Once the static friction has been overcome at all contact points, the gross slippage takes place. Incipient slippage is defined as the moment when the static friction at the final contact point is overcome.

To surmise, the primary approach of the model is embodied in the concept of the vertical virtual beam which is both compressible and bendable. As mentioned, the primary parameters taken into consideration are the sliding displacement $d(t)$ as a function of time and the five abovementioned forces. The preslip stage of the fingertip is characterized by the localized displacements of the individual contact points with the moment of incipient slippage ascertained when all contact points are in motion. The following section will explain the drawback of these limiting factors within the scope of this research work and provide possible amendments for it to be utilized.

5.1.2 Proposed Extension to Model

The main drawback for the model by Ho in the context of the present work is its inability to simulate transient normal forces which is the measured phenomenon of the proposed incipient slip detection approach (refer to Section 4.4). The normal force parameter F_i^n (see Figure 5.3) included in the model does not describe any transient behavior or exhibit oscillating values as it is the result of the monolithic grasping force which does not vary from beginning to end of slip. Consequently the model in its present form, though adequate for detection of incipient slip *indirectly* through correlated force measurements (i.e. measuring bending moments of centre virtual beam corresponding to LDP [125]), could not be utilized with the high-frequency vibration approach as described in Section 4.1 which requires identification of transient signals at specific frequency range and spectral power

characteristic of incipient slippage. In their follow-up work entitled ‘Development of a Novel Slip Haptic Display Device Based on the Localized Displacement Phenomenon’, Ho et al. [126] successfully utilized the said model to facilitate a haptic display device instead. Therefore the model must be augmented in order for it to be successfully utilized for the purpose of this work. The following sections will describe the proposed possible amendments that could be undertaken to introduce variance in normal force and the selected approach. The final portion will summarize the main points of the Section 5.1.2.

Amended Virtual Beam:

In order to allow for analysis of the microvibration phenomenon characteristic at the moment of incipient slippage, we propose an amendment to the above model in which a second set of spring-damper-mass is defined for modelling of vibration in each virtual beam. The initiation of mass sliding movement $d(t)$ will result in the lag at the contacting surface which acts as an initialized displacement condition. At the moment of localized slip for that individual contact point (i.e. $F_t^{fr} > F_t^n \mu$), the virtual beam will act like a freely vibrating cantilever beam as shown in Figure 5.4. Upon ‘release’ the virtual beam will vibrate freely before coming to a rest. The combinations of all the released beams’ vibrations contribute to the signal spectrum observed with a specific range and power associated with the moment when the final beam is released. The vibration is assumed to be along both the x (i.e. parallel to the surface) as well as the z (i.e. perpendicular to the surface) directions due to the coupled nature the vibration due to each virtual beam’s assumed rigid structure.

Figure 5.4 Vibration in 'released' virtual beam

For an individual beam, the force equation describing the frequency of the vibration is as follows:

$$\omega_d = \omega_n \sqrt{1 - \zeta^2} \text{ where } \zeta = \frac{c}{2\sqrt{km}} \text{ and } \omega_n = \sqrt{\frac{k}{m}} \quad \text{[5.9]}$$

where k , m and c corresponds to the stiffness, mass and damping of an individual beam.

Amplitude:

$$2 \times \sqrt{\left(\frac{x_0}{2}\right)^2 + \left(\frac{(\dot{x}_0 + \zeta \omega_n x_0)}{2\omega_d}\right)^2} \quad \text{[5.10]}$$

where x_0 – initial displacement, $\dot{x}_0$ – initial velocity.

Output for model extension: Amplitude and frequency

The primary trend as observed from the results which will be described in greater details in Section 5.2 is the increase in amplitude of vibration within the high band frequency starting from initial partial slippages reaching a maximum at the moment of incipient slippage.

Increase in amplitude of vibration:

For a singular beam, the initial condition of x_0 displacement is primarily consistent with the displacement $d(t)$ when condition defined by equation [5.4] is fulfilled i.e. the static friction for the said beam is exceeded. This condition is especially true for beams at the extreme peripheral i.e. beams $-N$ and N . In Figure 5.5, the time required from start of sliding motion to the localized slip of a particular beam is dependent on the position of the beam (i.e. the peripheral beams first and the beams close to the center last). Consequently, the sliding displacement $d(t)$ increases from the initial slip of peripheral beams at time T_{-N} to the slippage of the final beam at T_{N-3} which is directly correlated to the individual initial displacement condition for each beam i.e. $d(T_{-N}) < d(T_{N-3})$. This implies an increasing amplitude of vibration for each beam correlated to the sequence of its localized slip with the final beam having the highest amplitude which is coincident to incipient slippage. The maximum amplitude of the vibration could be calculated based on substitution of $x_0 = d(T_{n-3})$ and $x_0 = 0$ in equation [5.10].

Identification of frequency:

The frequency of the vibration is contributed by the vibration of individual beams upon moment of localized slip. Each beam's unique vibration is dependent on the individual damping and stiffness values as stated in equation [5.9]. The value of stiffness is calculated based on beam stiffness $k_i = \frac{3EI}{l_i^3} = \frac{Eqp^3}{4l_i^3}$ where q – width, q – thickness, E – the elastic modulus and l_i – the beam's free length.

Figure 5.5 A. LDP of contact point for each virtual beam, B. Moment when each contact point begins to move (Adapted from Ho [125])

5.1.3 Application of Amended Model within Proposed Framework

To recount, a critical task of the proposed framework in order to achieve the objective of providing sufficient grasping transparency is to overcome the intrinsic communication lag time between Master/local and Slave/remote sites and to achieve the highly critical time requirement in order to provide useful tactile information for restoring operator's innate grasping control (see Section 1.3). Pertaining to the latter, it is useful to recount that the first motor response following non-visible slips is circa 74 ms [37 & 43]. The framework achieved this through the Controller subsystem (see Figure 3.17) which will be described in the following section.

Controller

The main approach underlying the framework to achieve the abovementioned objective is through adoption of the hybrid shared control described earlier in Section 3.2.1 to be carried out through the Controller subsystem. The controller is tasked with two inter-related subtasks: i) facilitating autonomous response to imminent slip at the slave and ii) provide control to the Master interface in order for the operator to experience sufficient incipient slip-related tactile feedback. The overall control of grip force is adopted from Teshigawara et al. [48] position-based force control as shown in Figure 5.6. The desired force f_d is provided initially from the operator's input into the Master interface based on the force feedback provided F_{FS} (see Figure 5.6). Once object is grasped, sub-task i (i.e. for facilitating autonomous response) will come to play by maintaining the grip force control with an optimal safe region. This is achieved through incipient slip detection and increasing the desired force input through the following equation:

$\hat{f}_d = f_d + A \cdot D$, where f_d - initial force input, A - fixed constant, D – DWT power

as shown in the flowchart in Figure 5.7b.

Figure 5.6 A. Position-force control, B. Grip force control based on slip detection (Adapted from Teshigawara et. al [48])

Incipient slippage detection would be based on detection of peak value of threshold frequency as defined through the proposed extension model described earlier in Section 5.1.2 and monitored through the slip sensor. Throughout this period, subtask ii will maintain constant tactile feedback input through the slip display (refer to Section 3.1.2) based on a similar observation of the incipient slippage sensor.

5.1.4 Summary of Section

In this Section, the motivation and principle approach of the model adopted was elaborated along with the proposed extension to allow for calculation of threshold amplitude as well as frequency for incipient slip detection. The specific trend of increasing relative amplitude during the period of localized slip reaching a maximum at just prior of incipient slip, was identified through the proposed extension of the model. The proposed framework was then described with the application of the model for implementation of both haptic shared control and blend shared control elaborated. Subsequently, results obtained from the experiments undertaken to test the effectiveness of the incipient slip detection approach will be described in the following section.

5.2 Experimental Method and Results

In Chapter 4, the approach undertaken for incipient slip detection was described in detail together with the experimental setup (refer to Sections 4.3 and 4.4). A number of experiments were conducted to validate the approach and ascertain the

effectiveness. The step by step procedures of the experiment could be found in the beginning of Section 4.4.2, page 91 and shown in Figure 4.13. As mentioned in Step 6, the normal force data collected through the Flexiforce slip sensor are to be analyzed through a discrete wavelet transformation to obtain a time-frequency-amplitude/strength plot. The following section describes the wavelet transformation, both continuous and discrete, in greater detail:

Wavelet transformation

Wavelet transformation provides a means to describe the frequency of a non-stationary signal at the particular time in which it occurs. Unlike Fourier Transform which compares a signal with a series of sine/cos functions of various frequencies that stretches infinitely in time, the wavelet transformation allows for definition of frequency localized within a certain time period which is useful for analysis of signals with changing/dynamic or transient frequency content. Theoretically, it decomposes a signal into a set of mutually orthogonal wavelets, which themselves are scaled and shifted variants of a defined mother wavelet. Scaling refers dilation of the original mother wavelet which changes the wavelet center frequency¹ while shifting refers to translation of the said wavelet in the time domain. Figure 5.7 below depicts a graphic example of scaling and translation on a Daubechies 5 mother wavelet.

A. Mother Wavelet: Daubechies 5 Wavelet

B. Scaling & shifting of the Daubechies 5 Wavelet

Figure 5.7 A. Mother wavelet: Daubechies 5 Wavelet, B. Scaling & shifting of Daubechies 5 wavelet (adapted from <http://www.wavelet.org/tutorial/wbasic.htm>)

¹ Each wavelet is bandpass and characterized (thereby associated) through its center frequency.

By calculating the individual wavelet coefficient for each scale/shift combination of the mother wavelet, a time-scale function relating the wavelet to the signal is obtained. The primary equations required for wavelet transformation are listed as follows:

Haar wavelet (utilized in Discrete Wavelet Transformation):

$$\psi(t) = \begin{cases} 1 & \text{if } 0 \leq t \leq 1/2 \\ -1 & \text{if } 1/2 \leq t \leq 1 \\ 0 & \text{otherwise} \end{cases} \quad [5.11]$$

Morlet wavelet (utilized in Continuous Wavelet Transformation):

$$\psi(t) = \frac{1}{\sqrt[4]{\sigma^2\pi}} \exp\left(-\frac{t^2}{2\sigma^2} + j\omega_0 t\right) \quad [5.12]$$

The scaled (i.e. by 2^j) and shifted (i.e. by $2^j n$) general equation of a wavelet:

$$\left\{ \psi_{j,n}(t) = \frac{1}{\sqrt{2^j}} \psi\left(\frac{t-2^j n}{2^j}\right) \right\}_{(j,n) \in \mathbb{Z}^2} \quad [5.13]$$

The wavelet coefficient representing the correlation between the wavelet and the localized section of the signal $f(t)$ is calculated as follows:

$$\langle f, \psi_{j,n} \rangle = \int_{-\infty}^{+\infty} f(t) \psi_{j,n}(t) dt \quad [5.14]$$

Another important characteristic of wavelet is its intrinsically-joined time and frequency resolutions which related to the scale value as seen in Figure 5.8. Due to a wavelet's bandpass nature as well as its finite length in time, a small scale would imply a higher center frequency, lower frequency resolution and higher time resolution. In contrast, a large scale value would imply a lower center frequency, higher frequency resolution but a lower time resolution. To surmise, wavelet exhibits excellent time resolution with poor frequency resolution at high frequencies related to smaller-valued scales and vice-versa poor time resolution with excellent frequency resolution at lower frequencies related to larger-valued scales. The equivalent frequency F_{eq} of the individual wavelet is calculated as follows:

$$F_{eq} = \frac{C_f}{s\delta t} \quad [5.15]$$

where C_f —center frequency of mother wavelet, s - scaling factor and δt is the sampling period.

Figure 5.8 Inter-related time and frequency resolutions of wavelet at high and low frequencies

The main difference between the Continuous Wavelet Transformation (CWT) and Discrete Wavelet Transformation (DWT) is that in the former, both the scaling and translation values are continuous while in the latter, both the scaling and shifting are limited to being dyadic. In practical application, the DWT functions similar to a cascading series of filters. A non-stationary signal is fed into a pair of high and low pass filters which constitutes a level. Each level reduces the frequency by an octave while the number of samples is reduced by half as per Nyquist condition as seen in Figure 5.9 below.

Figure 5.9 Cascading filter bank of discrete wavelet transform

The following table matches the path to the frequency band of the signal sampled at 100kHz for DWT²:

Table 5.1: Path and associated frequency for DWT

Path	Frequency (kHz)	Path	Frequency (kHz)
0	0-50	0011	16.25-25
1	25-50	0010	12.5-16.25
01	25-50	0100	25-31.25
00	0-25	0101	31.25-37.5
001	12.5-25	0110	37.5-43.75
000	0-12.5	0111	43.75-50
010	25-37.5	00010	6.25-9.375
011	37.5-50	00011	9.375-12.5
0001	6.25-12.5	00000	0-3.125
0000	0-6.25	00001	3.125-6.25

The following section shows the results obtained from a trial run with the following parameters: i) initial normal force: 0.548N, ii) speed of descent: 0.587 mm/s. In Figure 5.10, the displacement, normal force and tangential force are plotted in green, white and red. The results obtained here will corroborate the trend hypothesized through the proposed extension of the model at the end of Section 5.1.2 (pg. 104).

Comment: As seen in Figure 5.11, the tangential force for initiating slip starts of at 1.68s before reaching a plateau at 1.87-1.88s. The plateau signifies the overcoming of static friction and the starting point of gross slip which coincides with incipient slip as observed in numerous other experiments [125 & 126]. Consequently, the period of localized slip up to incipient slippage would occur within this time period of 1.68s to 1.87s. This is validated from the plot in Figure 5.12 where a growing

² The limit on low pass filter leveling paths could be circumvented through arbitrary path decomposition method i.e. paths 10, 11, 101, 111....are able to be traversed to access narrower bands consisting the upper half frequencies 25-50kHz.

spike is observed in the DWT output for the frequency band 25kHz to 50 kHz within the period.

Figure 5.10 Complete plot of Normal Force, Tangential Load Force and Displacement for first trial at 0.548N normal force

Figure 5.11 Plot from 1.6s - 2s of Normal Force, Tangential Load Force and Displacement for first trial at 0.548N normal force

Figure 5.12 Plot of DWT amplitude for path 1 i.e. 25kHz – 50kHz

Figure 5.13 Complete plot of CWT

Figure 5.14 Plot of CWT from 1.6s to 2.19s

In the CWT plot (Figure 5.13), the spike is again observed within the same period of 1.68s to 1.87s. With reference to the magnified CWT plot in Figure 5.14, it can be observed that from the initiation of tangent force at 1.68s to induce slip, there is a gradual increase in amplitude for the vibration within the 25kHz-50kHz frequency band. The increase reaches a maximum at the point of incipient slippage at 1.87s. It could be inferred therefore that at the start of localized slippage initiates at a lower amplitude and the greatest intensity of vibration takes place once all the localized slippage have taken place into an amalgamated gross slip. This result is in line with the trend hypothesized through the proposed extension described in Section 5.1.2.

The following trials advance the earlier experiment by varying different parameters to ascertain the effectiveness of the incipient slip detection approach. The parameters are as follows: i) Speed of gripped surface, ii) normal grip force and iii) tangential load force. The following sections will describe each of the experiment conducted and the results obtained.

Speed of Gripped Surface

Three different speeds were tested: i) 1.35 mm/s, ii) 3 mm/s and iii) 10 mm/s at constant normal force of 1.13N, constant acceleration of 5.4 mm/s^2 and vertical displacement of about 0.3mm. The sampling rate for the piezoresistive sensor was 100 kHz. Only DWT graph of frequency with strongest signals were shown.

Key: White – Normal Force (Piezoresistive sensor output FlexiForce A201: $0.44\text{N} + 0.67\text{N/V} * (\text{measure} - 1.27\text{V})$)
 Red – Tangential Load Force (Futek LSB200: 2.17N/V)
 Green – Displacement (Keyence LK-G402: 0.5 mm/V)

i) 1.35 mm/s:

Figure 5.15 Complete plot of Normal Force, Tangential Load Force and Displacement (1.35 mm/s)

Figure 5.16 Breakdown of Tangential Load Force Phases (1.35 mm/s)

Comment: Figure 5.15 shows the complete plot for tangential force, normal force as well as displacement. In Figure 5.16 above, the evolution of the tangential load is shown as measured through a second Futek LSB load cell attached to the gripped object by a connector and held in place to the THK guide as shown in Figure 5.17. The initial state of the sensor was in tension with the gripped object pulling due to gravity. Decrease in the positive output (i.e. tension) is observed at time 1.76s which coincides with Step 4 extending to 1.81s before the output of the load cell is changed to negative (i.e. compression) due to inertia of the gripped object and movement of the connector/load cell. An increasing negative (i.e. compression) force was measured until a peak was obtained at 1.924s where static friction of sensing element/gripped object surface is overcome (at 0.76V which translates to 1.65N) and total slip was experienced. The displacement of the gripped object continues to the pre-programmed 0.3 mm as shown in Figure 5.18 below.

Figure 5.17 Alternate tangential force load cell placing

Figure 5.18 Breakdown of Tangential Load Force Phases Superimposed on Displacement (1.35 mm/s)

Comment: In Figure 5.18, it is observed that though Actuator B had been initiated at 1.76 s, actual displacement was only recorded at 1.81 s (i.e. when compressive force

was recorded at load cell). At 1.924s when point of peak compressive force was attained (i.e. static friction), the displacement was measured at 0.05 mm.

Figure 5.19 Breakdown of Tangential Load Force Phases Superimposed on Normal Force (1.35 mm/s)

Comment: In Figure 5.19, it is observed that there was a significant decrease in normal force between 1.81 s and 1.924 s (i.e. when static friction is overcome) from 1.15N to 0.99N where it remained more or less constant throughout. This is consistent with the results obtained by Teshigawara et al. in [48, 49, 108, & 110]. As stated in [113], the change in resistance occurs when a vertical deformation of the pressure conductive rubber is followed with a shear deformation resulting in a redistribution of the internal conductive particles eventually reaching equilibrium.

Figure 5.20 Close-up of DWT Output (Haar wavelet) for 1.6kHz-3.125kHz (1.35 mm/s)

Result: In Figure 5.20, it is shown that the DWT output of the incipient slip sensing element at 1.6 kHz – 3.125 kHz reaches a peak at 1.909s which is 0.005s prior to static friction being overcome and total slip taking place.

ii) 3 mm/s:

Figure 5.21 Complete plot of Normal Force, Tangential Load Force and Displacement (3 mm/s)

Figure 5.22 Breakdown of Tangential Load Force Phases (3 mm/s)

Comment: Figure 5.21 shows the complete plot for the outputs from the Flexiscan sensor (normal force), Futek load cell (tangential force) and Keyence Displacement Sensor (displacement). In Figure 5.22, decrease in the positive output (i.e. tension) is observed at time 2.37s which coincides with Step 4 extending to 2.41s before the output of the load cell is changed to negative (i.e. compression) due to inertia of the gripped object and movement of the connector/load cell as before. An increasing negative (i.e. compression) force was measured until a peak was obtained at 2.51s where static friction of sensing element/gripped object surface is overcome (at 1.71 N) and total slip was experienced. The displacement of the gripped object continues to the pre-programmed 0.3 mm as shown in Figure 5.23 below. The complete course of displacement for the gripped object as measured through the laser displacement sensor (and earlier set through the Galil Control System to complete a displacement of 0.3mm from the initial starting point).

Figure 5.23 Breakdown of Tangential Load Force Phases Superimposed on Displacement (3 mm/s)

Comment: In Figure 5.23, it is observed that actual displacement was only recorded at 2.41 s (i.e. when compressive force was recorded at load cell). At 2.51s when point of peak compressive force was attained (i.e. static friction), the displacement was measured at 0.0375 mm.

Figure 5.24 Breakdown of Tangential Load Force Phases Superimposed on Normal Force (3 mm/s)

Comment: In Figure 5.24, it is observed that there was a decrease in normal force between 2.41 s and 2.51 s (i.e. when static friction is overcome) from 1.12N to 1.06N where it remained more or less constant throughout.

Figure 5.25 Close-up of DWT Output (Haar wavelet) for 1.6kHz-3.125kHz (3 mm/s)

Result: In Figure 5.25, it is shown that the DWT output of the incipient slip sensing element at 1.6 kHz – 3.125 kHz reaches a peak at 2.49s which is 0.02s prior to static friction being overcome and total slip taking place.

10 mm/s:

Figure 5.26 Complete plot of Normal Force, Tangential Load Force and Displacement (10 mm/s)

Figure 5.27 Breakdown of Tangential Load Force Phases (10 mm/s)

Comment: Figure 5.26 shows the complete plot for the outputs from the Flexiscan sensor (normal force), Futek load cell (tangential force) and Keyence Displacement Sensor (displacement). In Figure 5.27, decrease in the positive output (i.e. tension) is observed at time 1.86s which coincides with Step 4 extending to 1.93s before the output of the load cell change to negative (i.e. compression) due to inertia of the gripped object and movement of the connector/load cell. An increasing negative

(i.e. compression) force was measured until the minimum output from the load cell was measured at 2.05s where static friction of sensing element/gripped object surface is overcome (at 1.63 N) and total slip was experienced. The complete course of displacement for the gripped object as measured through the laser displacement sensor (as set through the Galil Control System to complete a displacement of 0.3mm from the initial starting point) is shown in Figure 5.28.

Figure 5.28 Breakdown of Tangential Load Force Phases Superimposed on Displacement (10 mm/s)

Comment: In Figure 5.29, it is observed that actual displacement was only recorded at 1.93 s (i.e. when compressive force was recorded at load cell). At 2.05s when point of peak compressive force was attained (coinciding with the minimum point of the tangential force plot as seen in Figure 5.28), the displacement was measured at 0.035 mm.

Figure 5.29 Breakdown of Tangential Load Force Phases Superimposed on Normal Force (10 mm/s)

Comment: In Figure 5.29, it is observed that there was a decrease in normal force between 1.93 s and 2.05 s (i.e. when static friction is overcome) from 1.12N to 1.06N. Subsequently, an increased normal force was observed up to 1.35N which is an anomaly which may be due to the contact surfaces not being parallel. This could be explained due to possible movement of the Object Carriage Way configuration.

Figure 5.30 Close-up of DWT Output (Haar wavelet) for 3.125 kHz-6.25 kHz (10 mm/s)

Result: In Figure 5.30, it is shown that the DWT output of the incipient slip sensing element at 3.125 kHz – 6.25 kHz reaches a peak at 2.015s which is 0.035s prior to static friction being overcome and total slip taking place.

Normal Grip Force

Three different normal forces were tested: i) 0.90N, ii) 1.113N and iii) 1.631N at constant speed of 0.3mm/s. Acceleration was still pegged at 5 mm/s^2 with vertical displacement of 0.3mm. The sampling rate for the piezoresistive sensor was 100 kHz. As in the previous experiment, only DWT graphs of frequencies with strongest signals were shown.

Key: White – Normal Force (Piezoresistive sensor output FlexiForce A201: $0.44\text{N} + 0.67\text{N/V} \cdot (\text{measure} - 1.27\text{V})$)
 Red – Tangential Load Force (Futek LSB200: 2.17N/V)
 Green – Displacement (Keyence LK-G402: 0.5mm/V)

i) **0.90N:**

Figure 5.31 Complete plot of Normal Force, Tangential Load Force and Displacement (0.9N)

Figure 5.32 Breakdown of Tangential Load Force Phases (0.9N)

Comment: Figure 5.31 shows the complete plot for tangential force, normal force as well as displacement. In Figure 5.32, decrease in the positive output (i.e. tension) is observed at time 1.91s which coincides with Step 4 extending to 1.97s before the output of the load cell change to negative (i.e. compression) due to inertia of the gripped object and movement of the connector/load cell. An increasing negative (i.e. compression) force was measured until a minimum was reached at 2.05s where static friction of sensing element/gripped object surface is overcome (at 1.56 N) and total slip was experienced. The complete course of displacement for the gripped

object as measured through the laser displacement sensor (and earlier set through the Galil Control System to complete a displacement of 0.3mm from the initial starting point) is shown in Figure 5.33.

Figure 5.33 Breakdown of Tangential Load Force Phases Superimposed on Displacement (0.9N)

Comment: In Figure 5.33, it is observed that actual displacement was only recorded at 1.97 s (i.e. when compressive force was recorded at load cell). At 2.05s, when point of maximum compressive force was attained (coinciding with the minimum point of the tangential force plot as seen in Figure 5.20), the displacement was measured at 0.035mm.

Figure 5.34 Breakdown of Tangential Load Force Phases Superimposed on Normal Force (0.9N)

Comment: In Figure 5.34, it is observed that there was a decrease in normal force between 1.97 s and 2.07 s (i.e. when static friction is overcome) from 0.95N to 0.72N. A constant normal force was observed thereon.

Figure 5.35 Close-up of DWT Output (Haar wavelet) for 750 Hz-1.5 kHz (0.9N)

Result: In Figure 5.35, it is shown that the DWT output of the incipient slip sensing element at 750 Hz – 1.5 kHz reaches maximal amplitude twice outside the period of localized to incipient slippage between the start of compressive force at 1.97s to the when the compressive force reaches a maximum at 2.07s (i.e. coinciding with maximum static force). As this represents the only significant observation of increased amplitude of DWT, it was concluded that the incipient slip detection fail in this trial.

ii) 1.113N:

Figure 5.36 Complete plot of Normal Force, Tangential Load Force and Displacement (1.13N)

Figure 5.37 Breakdown of Tangential Load Force Phases (1.13N)

Comment: Figure 5.36 shows the complete plot for the outputs from the Flexiscan sensor (normal force), Futek load cell (tangential force) and Keyence Displacement Sensor (displacement). In Figure 5.37, decrease in the positive output (i.e. tension) is observed at time 3.07s which coincides with Step 4 extending to 3.12s before the output of the load cell change to negative (i.e. compression) due to inertia of the gripped object and movement of the connector/load cell. An increasing negative (i.e. compression) force was measured until a peak was obtained at 3.24s where

static friction of sensing element/gripped object surface is overcome (at 1.63 N) and total slip was experienced.

Figure 5.38 Close-up of DWT Output (Haar wavelet) for 3.1 kHz-6.25 kHz (1.13N)

Result: In Figure 5.38, it is shown that the DWT output of the incipient slip sensing element at 3.125 kHz – 6.25 kHz reaches a peak at 3.05s which is 0.19s prior to static friction being overcome and total slip taking place.

1.631N:

Figure 5.39 Complete plot of Normal Force, Tangential Load Force and Displacement (1.631N)

Figure 5.40 Breakdown of Tangential Load Force Phases (1.631N)

Comment: Figure 5.39 shows the complete plot for the outputs from the Flexiscan sensor (normal force), Futek load cell (tangential force) and Keyence Displacement Sensor (displacement). In Figure 5.40, decrease in the positive output (i.e. tension) is observed at time 2.51s which coincides with Step 4 extending to 2.547s before the output of the load cell change to negative (i.e. compression) due to inertia of the gripped object and movement of the connector/load cell. An increasing negative

(i.e. compression) force was measured until a peak was obtained at 2.685s where static friction of sensing element/gripped object surface is overcome (at 1.56 N) and total slip was experienced.

Figure 5.41 Close-up of DWT Output (Haar wavelet) for 3.1 kHz-6.25 kHz (1.631N)

Result: In Figure 5.41, it is shown that the DWT output of the incipient slip sensing element at 3.1 kHz – 6.25 kHz reaches a peak much later than the time static friction was overcome at 2.685s. As this represents the only significant observation of increased amplitude of DWT, it was concluded that the incipient slip detection fail in this trial.

Tangential Load Force

The tangential load force is varied by changing the acceleration parameter of Motor B. Three different accelerations were tested: i) 0.07 mm/s^2 , ii) 1 mm/s^2 and iii) 2.7 mm/s^2 at constant speed of 1 mm/s and normal force of 1.18 N . The vertical displacement was set at 1 mm . The sampling rate for the piezoresistive sensor was

100 kHz. Only DWT graph of frequency with strongest signals were shown (see Figures 5.43, 5.45 and 5.47).

Key: White – Normal Force (Piezoresistive sensor output FlexiForce A201: $0.44\text{N} + 0.67\text{N/V} * (\text{measure} - 1.27\text{V})$)

Red – Tangential Load Force (Futek LSB200: 2.17N/V)

Green – Displacement (Keyence LK-G402: 0.5mm/V)

i) 0.07 mm/s^2 :

Figure 5.42 Complete plot of Normal Force, Tangential Load Force and Displacement (0.07 mm/s^2)

Figure 5.43 Close-up of DWT Output (Haar wavelet) for 750 Hz-1.5 kHz (0.07 mm/s^2)

Result: In Figure 5.42, decrease in the positive output (i.e. tension) is observed at time 2.9s which coincides with Step 4 extending to 3.4s before the output of the load cell change to negative (i.e. compression) due to inertia of the gripped object and movement of the connector/load cell. An increasing negative (i.e. compression) force was measured until a peak was obtained at 4.7s where static friction of sensing element/gripped object surface is overcome (at 1.73 N) and total slip was

experienced. In Figure 5.43, it is shown that an increasing DWT output of the incipient slip sensing element at 750 Hz – 1.5 kHz was obtained starting at 4.5s (0.2s before 4.7s) reaching a peak at 5.7s.

ii) 1 mm/s²:

Figure 5.44 Complete plot of Normal Force, Tangential Load Force and Displacement (1 mm/s²)

Figure 5.45 Close-up of DWT Output (Haar wavelet) for 750 Hz-1.5 kHz (1 mm/s²)

Result: In Figure 5.44, decrease in the positive output (i.e. tension) is observed at time 2.3s which coincides with Step 4 extending to 2.4s before the output of the load cell change to negative (i.e. compression) due to inertia of the gripped object and movement of the connector/load cell. An increasing negative (i.e. compression) force was measured until a peak was obtained at 2.8s where static friction of sensing element/gripped object surface is overcome (at 1.73 N) and total slip was experienced. In Figure 5.45, it is shown that an increasing DWT output of the incipient slip sensing element at 750 Hz – 1.5 kHz was obtained starting at 2.75s (0.05s before 2.8s) reaching a peak at 3s.

iii) 2.7 mm/s²:

Figure 5.46 Complete plot of Normal Force, Tangential Load Force and Displacement (2.7 mm/s²)

Figure 5.47 Close-up of DWT Output (Haar wavelet) for 750 Hz-1.5 kHz (2.7 mm/s²)

Result: In Figure 5.46, decrease in the positive output (i.e. tension) is observed at time 2.55s which coincides with Step 4 extending to 2.7s before the output of the load cell change to negative (i.e. compression) due to inertia of the gripped object and movement of the connector/load cell. An increasing negative (i.e. compression) force was measured until a peak was obtained at 2.9s where static friction of sensing element/gripped object surface is overcome (at 1.73 N) and total slip was experienced. In Figure 5.47, it is shown that an increasing DWT output of the incipient slip sensing element at 750 Hz – 1.5 kHz was obtained starting at 2.75s (0.02s before 2.9s) reaching a peak at 3.1s.

5.2.1 Discussion

The results from the first trial conducted (pg. 114) clearly showed the trend of increasing amplitude of vibration at the higher band frequencies. The result obtained through DWT (see Figure 5.14) was further corroborated by the CWT analysis plot (see Figures 5.15 and 5.16). Consequently, the results obtained here clearly corroborated the hypothesis identified through the proposed model extension in Section 5.12. The subsequent trials to ascertain the efficiency and performance of the proposed incipient slip detection method described in Section 4.2 tested a total of three different parameters: i) slip speed of gripped of object, ii) normal grip force and iii) tangential load force/acceleration. Three different values (i.e. speed, force and acceleration) were tested for each parameter:

- i) Speed of gripped object: 1.35 mm/s, 3 mm/s and 10 mm/s
- ii) Normal grip force: 0.9N, 1.113N and 1.631N
- iii) Tangential load force/acceleration: 0.07 mm/s², 1 mm/s² and 2.7 mm/s²

The following table shows the overall results of all nine experiments:

Table 5.2 Tabulated results

Parameters varied	Value	Frequency (Hz)	Incipient slip time (s)	Overall slip time (s)	Time difference (s)
Speed of gripped object (mm/s)	1.35	1600-3125	1.9	1.924	0.024
	3	1600-3125	2.49	2.51	0.02
	10	3125-6250	2.01	2.05	0.04
Normal grip force (N)	0.9	NA	NA	NA	NA
	1.13	3125-6250	3.05	3.24	0.19
	1.631	NA	NA	NA	NA
Tangential load	0.07	750-1500	4.5	4.7	0.2

force/acceleration (mm/s ²)	1	750-1500	2.75	2.8	0.05
	2.7	750-1500	2.75	2.9	0.15

There were two failed attempts, both from varying normal forces (i.e. 0.9N and 1.631N). The specific discussions on the results of each parameter are made in the following sections:

Speed of gripped surface

Incipient slips prior to gross slips were successfully detected for all three magnitudes of speeds. The time advantage ascertained through the test ranged from 0.02s to 0.04s corresponding to 3 mm/s and 10 mm/s respectively. A higher frequency band was ascertained as the incipient slip detection frequency for the highest speed of 10 mm/s. A qualitative association with the model could be made here in that the higher speed would result in a higher frequency normal force variation under the assumption of homogeneous asperities frequency for the sliding surface. The best result obtained of 0.04s before total slip was for the maximum speed tested of 10 mm/s.

Normal grip force

Of the three values, incipient slip was only successfully detected for 1.13N value. This result could be rooted to the limitations of the Flexiforce A201 1lb rated piezoresistive sensor. Although the officially rated for 0 to approximately 4.5N, the calibration exercise revealed an effective transduction from just slightly under 0.5N to just over 2N with considerable non-response for forces beyond both ends as seen in the graph for load vs voltage for the FlexiForce A201 piezoresistive sensor in Figure 4.5 (pg.81). The failure to detect the lowest and highest magnitudes could allude to sensitivity for incipient slip detection being strongly correlated to the sensitivity for normal force for the A201 piezoresistive sensor. It is of note that for the remaining two parameters of speed and tangential load/acceleration where wholly successful incipient slip detection approach was attained, the normal forces were rated at 1.13N and 1.18N respectively close to the only positively detected value of 1.13N for this parameter. The result obtained for 1.13N was also the best

result obtained for the entire experiment with a 0.19s time difference from moment of total slip.

Tangential load force/acceleration

For all values tested, positive results were attained for the proposed incipient slip detection. The best result of 0.15s time difference from overall slip was attained for the maximum acceleration tested at 2.7 mm/s^2 . This result may allude to the role of tangential force/acceleration on the effectiveness of the incipient slippage detection approach.

5.2.2 Summary of Section

In this section, two sets of experimental results, first to corroborate the hypothesis identified through the proposed model extension and second to ascertain the effectiveness of the proposed incipient slippage detection approach were reported. The results from both the DWT and CWT analysis in the first experiment were clearly in line with the proposed model. The results from the second set of experiments evaluated on the performances of three different parameters namely speed of gripped object, normal grip force and tangential load force/acceleration. Positive results were obtained for seven out of the nine tested with the two failures coming from the minimum and maximum values for the normal grip force evaluation. Inherent limitation to range of the piezoresistive sensor utilized could offer a possible explanation for the failure to detect the normal force values.

5.3 Chapter Summarization

In the first half of this Chapter, Ho's [125] 2DBBM model for sliding deformable fingertip on surface was reviewed and the extension proposed in this work to allow for adaption of frequency-based incipient slippage detection approach was described. The original model consisting of virtual bendable and compressible beams was extended to allow for vibrations of individual beams at moment of localized slip to identify the frequencies characteristic of the moment of incipient slippage as well as the magnitude of vibration strength at said frequency. In the second half, the experiments conducted to corroborate the hypothesis identified through the proposed extension as well as ascertain effectiveness of the incipient

slippage detection approach were reported together with the significant results. The hypothesis was successfully corroborated with the result of the first experiment. In the second set of experiments, it was reported that in almost all of the tests conducted that the approach was positive in detection. In the next chapter, the salient points of this thesis will be recounted and possible further works pertaining to the research undertaken will be discussed.

Chapter 6

Conclusion and Further Works

In this research work the problem of impaired grasping within RMIS due to absence of tactile feedback during grasping is examined. Primarily a telerobotic system, the principle of the problem could be defined as the need to provide for grasping transparency in order to restore natural grasping to the surgeon operators during grasping and manipulation of tissue. Towards that end, it was established that a novel tactile feedback system is required to restore the intrinsic human grasp response, one focus specifically on restoration of tactile sensations at the local site and incipient slippage detection at the remote site. In practice, the manifest time delay within local-remote communications has to be mitigated to preserve the effective transparency. The main objective of this work is to develop a tactile feedback system-based solution for achieving grasp transparency in RMIS. Section 6.1 will reiterate and discuss the detailed objectives of this work. This is followed by a brief discussion of potential future developments in Section 6.2.

6.1 Conclusion

In Section 1.5 the following were listed down as objectives for this research work:

- **To characterize and ascertain the necessary parameters and events required during grasping of object.** Literature review pertaining to psychophysical studies conducted on active and passive manipulation of object and precision grip was undertaken to derive the necessary parameters and specifications required.
- **To review, analyze and evaluate current tactile feedback systems.** Literature review of available tactile feedback system to: i) assess suitable candidates, ii) establish the limits of current stage of development, and iii) identify possible improvement to facilitate adoption to intended solution.
- **To design appropriate tactile feedback system to facilitate solution.** Explore and implement tactile sensor to measure normal force and detect

localized slip events together with tactile display to replicate grip force as well as slip region growth during slip.

- **To formulate a detailed framework to achieve sufficient grasp transparency.** The main task of the framework is to overcome or mitigate the problem of inherent lag in communication time between remote and local sites.
- **To model incipient slip.** This is required to facilitate the function of the framework.

The following sub-sections will assess whether the research work has achieved its intended objectives.

To characterize and ascertain the necessary parameters and events required during grasping of object.

This objective was achieved in Section 1.3.1. The main mechanism behind optimal grasping when utilizing precision grip was identified through reviewing of literature pertaining to psychophysical studies of precision grip to be the early partial/incipient slip detections through the activation of FAI tactile afferents leading to the evocation of the automatic grip response. In Section 1.3.1, it was ascertained that the surface of contact on the glabrous skin of the human fingertip during grasp experience a strong normal force in the center (i.e. the stick area) and weaker forces in the periphery (i.e. slip area) due to the natural curvature of the fingers. In the event of incipient slip, the detection is facilitated by growth of the area of slip region from the periphery towards the center and increasing occurrences of partial slips within the region. The maximum growth speed was found to be 50mm/s corresponding to an initial low (normal) grip force of 1N which slowed down exponentially once a grip force of over 5N was achieved corresponding to a maximum vertical skin deformation measuring 3mm. Section 1.1.2 established that the grip force range for grasping and manipulation of tissue typically averaged between 0 to 5N although forces as high as 40N have been measured.

To review, analyze and evaluate the current state of tactile feedback systems.

This objective was achieved in Chapters 2, 3, 4 and 5. A comprehensive definition of tactile feedback system strictly on the basis of MIS/RMIS application

followed by the 2-class categorization approach of dynamic and static derived from FAI and SAI tactile afferents in Sections 2.2.1 and 2.2.2 has helped focus the review of tactile feedback systems to cater to the requirements for facilitation of grasping within RMIS. Following that it was established that there was a dearth of systems that fall under the dynamic category, a class of tactile feedback system aligned to the requirements of the current work. The sole representative within the category, the Multielement Tactile Feedback System [47 & 54], was found to be wanting in its tactile sensing component in that it features a static tactile sensor instead of a dynamic variant able to capture transient incipient slippage during grasping. To surmise, the review method and categorization approach established in of Section 2.2.2 had help identify a gap in the technology with regards to an absence of a tactile feedback system which could detect incipient slippage.

To address this gap, the planned tactile sensor component of the proposed tactile feedback system designed on the basis of a CoP and Slip sensor elements based on Teshigawara et. al's [48] work was described in Section 3.1.1. The main principle of detection of the incipient slippage consisting of detection of high-frequency vibration through pressure conductive rubber was described in Section 4.2.1. This was followed up with the prototype developed in this work based upon the commercially available FlexiForce A201 piezoresistive force sensor which was reported upon in Section 4.2.2. Finally, the prototype sensing element was put to the test within an experimental setup described in Section 4.3. The effectiveness and rigour of the prototype was tested for varying slip speed, normal grip force and tangential load as described in Section 5.2. The results obtained showed failure to detect incipient slippage for only 2 out of the 9 tests, primarily due to the limited force range of the 1lb-rated FlexiForce sensor, with a maximum advantage of 200 ms detection before gross slip scored and an average detection advantage of 100 ms overall (refer to Table 5.1).

Although the results here represents a modest detection time for overall slip, the significance is the greater flexibility offered in terms of applying various time-mitigating approaches. When contrasted with other contemporary works [48, 112-114], the results obtained here were seen to be comparable (see Figures 6.1 & 6.2). In the work reported by Teshigawara et. al [48] from which Figure 6.2 was adapted

from, an effective control algorithm for a highly effective and sophisticated grip force control of a robot hand was implemented. It was demonstrated that the hand could adjust its grip to maintain balance of a cup with plastic particles being poured into it on the fly as shown in Figure 6.3. Consequently, it is shown that the detection time afforded through incipient slip detection could be utilized through fully autonomous control for effective grip force control.

Figure 6.1 A. Discrete Wavelet Transform (DWT) for object slip with initial normal force of 2N, B. DWT for object slip with initial normal force of 3N (Adapted from Teshigawara et. al [112])

Figure 6.2 DWT for object slip experiment with threshold defined for 0.4×10^{-4} (Adapted from Teshigawara et. al [48])

Figure 6.3 Implementation of grip force control with incipient slip detection
(Adapted from Teshigawara et. al [48])

To design appropriate tactile feedback system to facilitate solution.

This objective was achieved in Section 3.1. The gap in tactile feedback system pertaining to the absence of one incorporated with an incipient slippage tactile sensor was addressed with the proposed design of a complete system equipped with both incipient slippage tactile sensor as well as tactile display. The sensor and display designs were fully described in Sections 3.1.1 and 3.1.2. The pressure conductive rubber was utilized as the basis of the former for both incipient slippage detection as well as monolithic force measurement. As for the display, the pneumatic balloon tactor interface was designed to facilitate incipient slippage tactile feedback through replication of growing slip region on the fingertip with the force feedback provided for by the actuated force display. The structure of the tactile display was designed based on the EndoWrist manipulator of the da Vinci RMIS in view of possible future integration. Full control scheme for the tactile display was shown and described in Section 3.1.2 while the integrated control scheme was shown and described in Section 3.1.3. The design of the incipient slippage tactile feedback system represents the first of this work's claim of contribution with no complete design of a tactile feedback system for incipient slippage being available in the current inventory based on the author's knowledge.

To formulate a detailed framework to achieve sufficient grasp transparency.

This objective was achieved in Section 3.2. In order to achieve sufficient grasp transparency, the primary objective of the framework is to mitigate the inherent time delay in remote-local communications as well as other processing delays. Towards that end, it was described in Section 3.2.1 that the shared control architecture was leveraged for a hybrid shared control in which a haptic shared control element is utilized to provide continuous tactile feedback at the local site while the generic input-mixing/blend shared control was employed to generate autonomous control at the remote site. The method that was implemented for the autonomous control as well as to effect the continuous tactile feedback was described in Section 5.1.3 in which the proposed model for incipient slip would play the critical role in effecting it. The hybrid shared control framework represents the second of this work's claim of contribution with no other similar framework for tactile feedback system in literature based on the author's knowledge.

To model incipient slip

This objective was achieved in Section 5.1. The model was based on and adapted from Ho's Two Dimensional Beam Bundle Model (2DBBM) in which compressible and bendable virtual beam are utilized to break the monolithic sliding surface with a deformable finger into smaller parts to facilitate analysis and modeling of partial slips leading to incipient slippage. The amendment proposed in this work to allow for variation in transient normal force in place of the monolithic normal grip force of the previous model proposes homogenous asperities on the sliding surface with equally spaced peaks and valleys to generate the high-speed transient variations in normal force. Consequently with the amendment, 2DBBM could be applied for vibration-based incipient slippage detection approaches in which a theoretical incipient slippage detection frequency could be predicted. The amended 2DBBM model for vibration-based incipient slippage detection represents the third and final claim of contribution with no other similar model in literature based on the author's knowledge.

6.2 Further Work

The direction in which the future work takes could be divided into the following four headings:

1. Manufacturing, testing and implementation of tactile sensor component from FlexiForce force sensor including microfabrication.
2. Manufacturing, testing and implementation of tactile display component.
3. Integration of system onto a master-slave platform.
4. Testing of the proposed hybrid shared control framework

Manufacturing, testing and implementation of tactile sensor component

This would involve first and foremost a more detailed and accurate characterization of the FlexiForce force sensor which includes calibration with respect to total force measured and output voltage. Manufacturing would involve microfabrication of electrical readout circuits which includes deposition of Au/Cr traces through sputtering or e-beam deposition onto the Kepton polyimide material, baking and curing as well as dicing. The final manufacturing step involves integrating the circuit onto the customized FlexiForce force sensor to form the in-house CoP and slip sensors prior to testing the characteristic electrical response to slip/grip force as well as determining hysteresis. The testing of the sensor would involve updating and upgrading the test setup which consist of (amongst others) improving the motion control to enable more precise velocity and displacement specifications .

Manufacturing, Testing and Implementation of Tactile Display Component

For the grip force display, this would involve initially the fabrication of the mechanical links required, purchase of spring with the necessary spring constant in addition to characterization of the linear actuator. The system would then be integrated and tested. For the slip display, the fabrication of the onsite interface would involve constructing a mould for the PDMS substrate as well as microfabrication processes for making the balloon-based tactor. The processes involve include spin-coating, degassing as well as baking and curing. Once assembled, the interface would require integration with the planned pneumatic system which would consist of two proportional pressure regulators (upstream and downstream) as well as a 3/2 valve to be able to control both expansion and contraction of balloon-based tactor.

Integration of system onto a master-slave platform

A master-slave platform needs to be selected (either by choosing an existing platform or designing a simple system in-house) to allow for the integration of the tactile sensing, tactile display and control elements of the proposed tactile feedback system. The integrated system would need to be tested for stability and functionality for the purpose of conducting experiments for the optimal grasping.

Testing of proposed hybrid shared control framework.

Once a master-slave platform has been established, experiments are to be conducted to test the effectiveness of the proposed hybrid shared control framework in mitigating the remote-local time delay as well as in the provision of continuous tactile feedback. A preliminary study could be conducted to further test the rigour and effectiveness of the model developed as it would play a critical role in facilitating the hybrid shared control. Subsequently, a control network to effect the system-wide framework must be designed and implemented for initially offline tests followed by online implementation. A possible candidate would be embedded NI control system which affords integration with various sensors, actuators and other peripherals as well as provide a convenient software interface in the form of the LabView application. Preliminary studies must be conducted for each component (i.e. tactile sensing and tactile display) prior to integration. Prior to physical implementation of the system, a software based model of the integrated incipient slippage tactile feedback system could be implemented to allow for insights as well as offer possible solution to potential problem. Once implemented, effective approaches to measuring effectiveness that must include speed of response, level of ease and ‘naturalness’ for operator as well as avoidance of damage must be designed.

6.3 Concluding remarks

The problem of impeded natural grasping within the telerobotic RMIS was investigated in this work. A solution based on a novel incipient slippage tactile feedback system was proposed. The following five sub-objectives defining the scope of the work were proposed and successfully achieved:

- i. The characterization and ascertainment of the necessary parameters and events during grasping of object with a focus of precision grip.
- ii. The review, analysis and evaluation of current state of tactile feedback system development and technology.
- iii. The design of the incipient slippage tactile feedback system.
- iv. The formulation of an overall framework to facilitate the effective application of the incipient slippage tactile feedback system in maintaining sufficient grasp transparency.
- v. The modeling of the incipient slip with focus on application of vibration-based incipient slippage detection approach.

Three contributions were claimed to be made in the course of this work namely:

- a. The design for incipient slippage tactile feedback system.
- b. The hybrid shared control framework.
- c. The amended 2DBBM model for incipient slip prediction.

An incipient slip sensing element based on the piezoresistive FlexiForce A201 force sensor was designed, constructed and tested and the results reported. Possible configurations to test effectiveness of the framework were proposed as future works along with construction of proposed tactile sensor and tactile display. It is hoped that the establishment of the tactile feedback system would allow one to test various control configurations for RMIS as well as telerobotics in general.

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Appendix

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Appendix A FlexiForce Load Sensor

Appendix B Futek Load Cell

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Appendix F Advanced Motion Controls (AMC) Analog DC Drives

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Appendix A

FlexiForce Load Sensor

The datasheets for Tekscan Inc. FlexiForce A201 Standard Force and Load Sensor 0-1 lb utilized in this work is listed in this appendix.

Physical Properties

Thickness	0.208 mm (0.008 in.)
Length	197 mm (7.75 in.)* <i>optional trimmed lengths: 152 mm (6 in.), 102 mm (4 in.), 51 mm (2 in.)</i>
Width	14 mm (0.55 in.)
Sensing Area	9.53 mm (0.375 in.) diameter
Connector	3-pin Male Square Pin (center pin is inactive)
Substrate	Polyester (ex: Mylar)
Pin Spacing	2.54 mm (0.1 in.)

* Length does not include pins, please add 31.75 mm (0.25 in.) for pin length to equal a total length of 203.2 mm (8 in.).

Standard Force Ranges (as tested with circuit shown below)

0 - 1 lb. (4.4 N)
0 - 25 lb. (110 N)
0 - 100 lb. (440 N)*

In order to measure forces above 100 lb (up to 1000 lb), apply a lower drive voltage (-0.5 V, -0.10 V, etc.) and reduce the resistance of the feedback resistor (1kΩ min.) Conversely, the sensitivity can be increased for measurement of lower forces by increasing the drive voltage or resistance of the feedback resistor.

Recommended Circuit

- * Supply Voltages should be constant
- ** Reference Resistance R_s is 1kΩ to 100kΩ
- Sensor Resistance R_s at no load is >5MΩ
- Max recommended current is 2.5mA

Typical Performance

Linearity (Error)	< ±3%
Repeatability	< ±2.5% of full scale
Hysteresis	< 4.5 % of full scale
Drift	< 5% per logarithmic time scale
Response Time	< 5μsec

Operating Temperature 15°F - 140°F (-9°C - 60°C)

*Force reading change per degree of temperature change = ±0.2%/°F (0.36%/°C)

**For loads less than 10 lbs., the operating temperature can be increased to 165°F (74°C)

High-temp model (HT201) available, functioning in environments up to 400°F (204°C)

Evaluation Conditions

Line drawn from 0 to 50% load
Conditioned sensor, 80% of full force applied
Conditioned sensor, 80% of full force applied
Constant load of 25 lb (111 N)
Impact load, output recorded on oscilloscope
Time required for the sensor to respond to an input force

Tekscan, Inc. 307 West First Street South Boston, MA 02127-1309 USA tel: 617.464.4500/800.248.3669 fax: 617.464.4266
e-mail: marketing@tekscan.com URL: www.tekscan.com

Rev K_11.22.11

Appendix B

Futek Load Cell

The load cell utilized is comprised of an S-Beam load cell component powered through an integrated amplifier/break-out circuit component. The datasheets: i) Futek Model LSB200 S-Beam Load Cell (5 lb) and ii) CSG 110 Amplifier are listed in the following subsections.

B.1 Futek Model LSB200 S-Beam Load Cell (5 lb)

B.2 CSG 100 Amplifier

FUTEK MODEL CSG110

CSG110 is an In-Line instrument that amplifies any full bridge strain gauge sensor with a mV/V output. The model enables voltage and current outputs, and features a built-in regulated bridge excitation source at two ranges. The standard CSG110 is offered with a 35mm DIN Rail Clip and a DB9 male and female connector to interface with sensors and external devices.

This model is also available in an OEM version for high volume applications. The CSG110 is designed and manufactured by FUTEK in the USA. To learn more, visit our website at www.futek.com/csg

General purpose 35mm DIN rail amplifier module, DC powered, universal strain gauge signal conditioner

PRODUCT HIGHLIGHTS

- Bipolar Output, Differential Input
- ± 5 or ± 10 VDC Outputs, Unipolar Bidirectional Voltage (0-5-10 VDC) also available
- 0-20 mA, 4-20 mA, 0-16 mA, 5-25 mA, Bidirectional Current (4-12-20 mA) DIP Switch Selectable Output
- Bridge Excitation Selectable 5 or 10 VDC
- Ranges: 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 10.0 mV/V (DIP Switch Selectable)
- Interchangeable Socket Mounted 60.4K Shunt Cal
- Externally Accessible Shunt Cal Activation Button
- Externally Accessible Span and Offset adjustments Resistor Locations
- Sensor Polarity Reversal DIP Switch
- Weight: 1.6 oz (45 g)

1

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Drawing Number: F11045-M

FUTEK
ADVANCED SENSOR TECHNOLOGY, INC.

Sensor Solution Source

10 Thomas, Irvine, CA 92618 U.S.A. | T: 949.465.0900 | F: 949.465.0905

www.futek.com | futek@futek.com

DIMENSIONS INCH [mm]

- 1. Current Switches
- 2. Shunt Button
- 3. Span Potentiometer
- 4. Zero Potentiometer
- 5. Bandwidth Switch
- 6. Ranges Switches
- 7. Polarity Switch
- 8. Excitation Switch

MALE DB 9 - POWER SIDE

# PIN	WIRING CODE	CABLE COLOR CODE
9	POWER SUPPLY	RED
8	SIGNAL OUT (VOLTAGE)	GREEN
7	GROUND	ORANGE
6	GROUND	BLACK
5	GROUND	N/A
4	GROUND	N/A
3	GROUND	N/A
2	GROUND	BLUE
1	SIGNAL OUT (CURRENT)**	WHITE

FEMALE DB 9 - SENSOR SIDE

# PIN	WIRING CODE
1	+ EXCITATION*
2	+ SIGNAL
3	- SIGNAL
4	- EXCITATION*
5	GROUND
6	GROUND
7	GROUND
8	GROUND
9	GROUND

* FOR 6 WIRE SENSOR CONNECT +SENSE TO +EXCITATION AND -SENSE TO -EXCITATION OR GROUND
**ONLY AVAILABLE WITH CURRENT OUTPUT OPTION

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ENVIRONMENT

Parameter	Min	Typical	Max	Unit
Operating Temperature*	32		158	F°
	0		70	C°
Storage Temperature	-40		185	F°
	-40		85	C°
Relative Humidity: 95% at 100 °F [39° C]				
IP Rating: IP31				

*Extended Operating Temperature -40 to 185°F [-40 to 85°C] Available Upon Request

VERSIONS

# Item	Bandwidth	Output
FSH01449	1 kHz	±5 VDC, ±10 VDC, 0-20 mA, 4-20 mA, 0-16 mA, 5-25 mA
FSH03546	1 kHz	±5 VDC, ±10 VDC
QSH00602⁽¹⁾	10 kHz	±5 VDC, ±10 VDC, 0-20 mA, 4-20 mA, 0-16 mA, 5-25 mA
QSH01498⁽²⁾	25 kHz	±5 VDC, ±10 VDC, 0-20 mA, 4-20 mA, 0-16 mA, 5-25 mA
FSH03676	1 kHz	0-2.5-5 VDC, 0-5-10 VDC, 4-12-20 mA
OEM Version Available - Contact Factory		

ELECTRICAL SPECIFICATIONS

Parameter	Min	Typical	Max	Unit
Power Supply ⁽³⁾	14		26	VDC
Current Dissipation ⁽⁴⁾		30		mA
Output Impedance (voltage)	1000			Ohms
Output Impedance (current)			500	Ohms
Sensor Impedance	100			Ohms
Bandwidth	1000		25000	Hz
Common Mode Rejection Ratio	120			dB
Noise		15		mV p-p
Output Span Range	-10		10	% of Rated Output
Output Zero Range	-10		10	% of Rated Output
Gain Drift with Temperature	-25	X	25	PPM of FSR
Gain Non-Linearity	-0.001	X	0.001	% of FSR
Zero Drift with Temperature	-25	X	25	PPM of FSR

(1) Only for sensitivity of 1 mV/V or greater

(2) Only for sensitivity of 1.5 mV/V or greater

(3) Minimum power supply varies for OEM models

(4) No load apply (input or output)

NOTES

- Adjusting Zero Will Not Affect Calibration
- Adjusting Span Will Affect Calibration
- Power Supply Must Source 150 mA Minimum
- Carefully Remove Cover To Access Dip Switches

WARNING: Do Not Connect Device To Power Supply When Power Supply Is Already On!

ISO 9001:2008

ISO 17025

US Manufacturer

Global Supplier

3

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Drawing Number: F11045-M

Appendix C

LabView Programs

Two applications: i) Measurement of Normal Grip Force, Tangential Load Force and Displacement application and, ii) Discrete Wavelet Transformation (DWT) application were programmed in LabView. The former was utilized to provide online measurement/monitoring and external file storage while the latter was used to execute DWT with data stored in the external file. The block diagrams for each application will be shown in the following subsections.

C.1 LabView Code for Online Measurement of Normal Grip Force, Tangential Load Force and Displacement Application

The block diagram code is shown in Figure A.1 below:-

Figure A.1 LabView code block diagram for Measurement of Normal Grip Force, Tangential Load Force and Displacement

C.2 LabView Code for Discrete Wavelet Transformation (DWT) Application

The block diagram code is shown in Figure A.1 below:-

Figure A.2 LabView code block diagram for DWT Application

Appendix D

Faulhaber DC Minimotor

The DC servomotor setup is comprised of three components: i) Faulhaber 22/6, 185:1 gearhead, ii) Faulhaber IE2-512 encoder and, iii) Faulhaber 224U0240SR DC motor. The datasheets for the aforementioned gear, encoder and DC motor are listed in the following subsections.

D.1 Faulhaber 22/6, 185:1 Gearhead

Hybrid Gearheads

0,4 Nm

For combination with
DC-Micromotors: 2224, 2230, 2232, 2233
DC-Motor-Tacho Combinations: 2251

Series 22/6

	22/6
Housing material	Plastic
Geartrain material	metal/plastic
Recommended max. input speed for:	
– continuous operation	4 000 rpm
Backlash, at no-load	≤ 3°
Bearings on output shaft	preloaded ball bearings
Shaft load, max.:	
– radial (7 mm from mounting face)	≤ 20 N
– axial	≤ 5 N
Shaft press fit force, max.	≤ 50 N
Shaft play (on bearing output):	
– radial	≤ 0,02 mm
– axial	≤ 0 mm
Operating temperature range	– 30 ... + 85 °C

Specifications

reduction ratio (nominal)	weight without motor g	length without motor L2 mm	length with motor				output torque		direction of rotation (reversible)	efficiency %
			2224 R L1 mm	2230 F L1 mm	2232 R L1 mm	2233 F L1 mm	M max. mNm	M max. mNm		
14,6 :1	32	59,4	59,9	65,7	67,9	68,3	400	600	≠	80
20,4 :1	32	59,4	59,9	65,7	67,9	68,3	400	600	≠	80
34 :1	32	59,4	59,9	65,7	67,9	68,3	400	600	=	75
47,6 :1	32	59,4	59,9	65,7	67,9	68,3	400	600	=	75
79,4 :1	34	59,4	63,1	68,9	71,1	71,5	400	600	≠	70
111 :1	34	59,4	63,1	68,9	71,1	71,5	400	600	≠	70
185 :1	36	59,4	66,3	72,1	74,3	74,7	400	600	=	65
259 :1	36	59,4	66,3	72,1	74,3	74,7	400	600	=	65
432 :1	38	59,4	69,5	75,3	77,5	77,9	400	600	≠	60
605 :1	38	59,4	69,5	75,3	77,5	77,9	400	600	≠	60
1 009 :1	40	59,4	72,7	78,5	80,7	81,1	400	600	=	55
1 412 :1	40	59,4	72,7	78,5	80,7	81,1	400	600	=	55
2 354 :1	42	59,4	75,9	81,7	83,9	84,3	400	600	≠	50
3 295 :1	42	59,4	75,9	81,7	83,9	84,3	400	600	≠	50

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D.2 Faulhaber IE2-512 Encoder

Encoders

Magnetic Encoders

Features:
64 to 1 024 Lines per revolution
2 Channels
Digital output

Series IE2 – 1024

		IE2 – 64	IE2 – 128	IE2 – 256	IE2 – 512	IE2 – 1024	
Lines per revolution	N	64	128	256	512	1 024	channels
Signal output, square wave		2					V DC
Supply voltage	V _{DD}	4,5 ... 5,5					mA
Current consumption, typical (V _{DD} = 5 V DC)	I _{DD}	typ. 6, max. 12				typ. 8,5	mA
Output current, max. ¹⁾	I _{OUT}	5					mA
Phase shift, channel A to B	φ	90 ± 45					°
Signal rise/fall time, max. (C _{LOAD} = 50 pF)	t _r /t _f	0,1 / 0,1					µs
Frequency range ²⁾ , up to	f	20	40	80	160	300	kHz
Inertia of code disc ³⁾	J	0,09					gcm ²
Operating temperature range		– 25 ... + 85					°C

¹⁾ V_{DD} = 5 V DC: Low logic level < 0,5 V, high logic level > 4,5 V: CMOS and TTL compatible

²⁾ Velocity (rpm) = f (Hz) × 60/N

³⁾ For the brushless DC-Servomotors the Inertia of code disc is J = 0,14 gcm²

Ordering information

Encoder	number of channels	lines per revolution	In combination with:
IE2 – 64	2	64	DC-Micromotors 1336 ... CXR, 1516 ... SR, 1524 ... SR, 1717 ... SR, 1724 ... SR, 1727 ... C, 1741 ... CXR 2224 ... SR, 2232 ... SR, 2342 ... CR, 2642 ... CR, 2657 ... CR, 3242 ... CR, 3257 ... CR, 3272 ... CR 3863 ... C, 3863 ... CR Brushless DC-Servomotors 1628 ... B, 2036 ... B, 2057 ... B, 2444 ... B
IE2 – 128	2	128	
IE2 – 256	2	256	
IE2 – 512	2	512	
IE2 – 1024	2	1024	

Features

These Incremental shaft encoders in combination with the FAULHABER DC-Micromotors and Brushless DC-Servomotors are used for the indication and control of both shaft velocity and direction of rotation as well as for positioning.

The encoder is integrated in the DC-Micromotors SR-Series and extends the overall length by only 1,4 mm. Built-on option for DC-Micromotors and Brushless DC-Servomotors.

Hybrid circuits with sensors and a low inertia magnetic disc provide two channels with 90° phase shift.

The supply voltage for the encoder and the DC-Micromotor as well as the two channel output signals are interfaced through a ribbon cable with connector.

Details for the DC-Micromotors and suitable reduction gearheads are on separate catalogue pages.

Output signals / Circuit diagram / Connector information

For notes on technical data and lifetime performance refer to "Technical Information".
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D.3 Faulhaber 224U0240SR DC Motor

DC-Motors

Precious Metal Commutation

5 mNm

For combination with
Gearheads: 20/1, 22E, 22/2, 22/5, 22/6, 23/1, 38/3
Encoders: IE2 – 16 ... 512, HE2-16

Series 2224 ... SR

		2224 U	003 SR	006 SR	012 SR	018 SR	024 SR	036 SR	
1	Nominal voltage	U _N	3	6	12	18	24	36	Volt
2	Terminal resistance	R	0,56	1,94	8,71	17,50	36,30	91,40	Ω
3	Output power	P _{2 max}	3,92	4,55	4,05	4,54	3,88	3,46	W
4	Efficiency	η _{max}	80	82	82	82	81	80	%
5	No-load speed	n ₀	8 100	8 200	7 800	8 100	7 800	7 800	rpm
6	No-load current (with shaft ø 2,0 mm)	I ₀	0,066	0,029	0,014	0,010	0,007	0,005	A
7	Stall torque	M _{st}	18,5	21,2	19,8	21,4	19,0	16,9	mNm
8	Friction torque	M _f	0,23	0,2	0,2	0,21	0,2	0,22	mNm
9	Speed constant	k _n	2 730	1 380	657	454	328	219	rpm/V
10	Back-EMF constant	k _c	0,366	0,725	1,520	2,200	3,040	4,560	mV/rpm
11	Torque constant	k _{tr}	3,49	6,92	14,50	21,00	29,10	43,50	mNm/A
12	Current constant	k _i	0,286	0,144	0,069	0,048	0,034	0,023	A/mNm
13	Slope of n-M curve	Δn/ΔM	438	387	394	379	411	462	rpm/mNm
14	Rotor Inductance	L	11	45	200	450	800	1 800	μH
15	Mechanical time constant	T _m	11	11	11	11	11	11	ms
16	Rotor inertia	J	2,4	2,7	2,7	2,8	2,6	2,3	gcm ²
17	Angular acceleration	α _{max}	77	78	74	77	74	74	·10 ³ /rad/s ²
18	Thermal resistance	R _{th1} / R _{th2}	5 / 20						K/W
19	Thermal time constant	T _{wt1} / T _{wt2}	6,8 / 440						s
20	Operating temperature range:								
	– motor		– 30 ... + 85 (optional – 55 ... + 125)						°C
	– rotor, max. permissible		+125						°C
21	Shaft bearings		sintered bronze sleeves (standard)		ball bearings (optional)		ball bearings, preloaded (optional)		
22	Shaft load max.:		2,0		2,0		2,0		mm
	– with shaft diameter		1,5		8		8		N
	– radial at 3 000 rpm (3 mm from bearing)		0,2		0,8		0,8		N
	– axial at 3 000 rpm		20		10		10		N
	– axial at standstill								
23	Shaft play:								
	– radial	≤	0,03		0,015		0,015		mm
	– axial	≤	0,2		0,2		0		mm
24	Housing material		steel, black coated						
25	Weight		46						g
26	Direction of rotation		clockwise, viewed from the front face						
Recommended values - mathematically independent of each other									
27	Speed up to	n _{0 max}	8 000	8 000	8 000	8 000	8 000	8 000	rpm
28	Torque up to	M _{2 max}	5	5	5	5	5	5	mNm
29	Current up to (thermal limits)	I _{a max}	2,200	1,200	0,570	0,400	0,280	0,180	A

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Appendix E

Galil Control Card

Galil Control Card system is comprised of a DMC-18x2 Series PCI bus Series, 1-4 axes interfaced with a PC and an external ICM 2900 Interconnect Module acting as a breakout hub interfacing with the drivers, power supply and actual DC motors. The datasheets for each is listed in the following subsections.

E.1 Galil DMC-18x2 Series PCI-bus Control Card

Product Description

The DMC-18x2 Series are PCI bus motion controllers for single and multi-axis applications. The Econo Series is designed for the most cost-sensitive applications.

To minimize cost, the following features are not available on the DMC-18x2: five through eight axes of control, optical isolation on inputs, uncommitted analog inputs, dual encoder inputs, and the auxiliary FIFO and DPRAM communication channel.

The DMC-18x2 incorporates a 32-bit microcomputer and provides advanced features such as PID compensation with velocity and acceleration feedfor-

DMC-1842 4-axis
PCI controller

ward, memory with multitasking for simultaneously running up to eight programs, and uncommitted I/O for synchronizing motion with external events. Modes of motion include point-to-point positioning, jogging, linear and circular interpolation, contouring, electronic gearing, and electronic cam.

Like all Galil controllers, the DMC-18x2 motor controllers use a simple, intuitive command language which makes them very easy to program. GalilTools software further simplifies system set-up with "one-button" servo tuning and real-time display of position and velocity information.

Features

- PCI card in 1- through 4-axis versions: DMC-18x2 where x=1,2,3,4 axes
- User-configurable for stepper or servo motors on any combination of axes. Optional firmware for piezo-ceramic motors. Configurable for sinusoidal commutation
- Accepts up to 12 MHz encoder frequencies for servos. Outputs up to 3 MHz for stepper motors
- PID compensation with velocity and acceleration feedforward, integration limits, notch filter and low-pass filter
- Modes of motion include jogging, point-to-point positioning, contouring, linear and circular interpolation, electronic gearing and ECAM. Features elliptical scaling, slow-down around corners, infinite segment feed, and feedrate override
- Over 200 English-like commands including conditional statements and event triggers
- Non-volatile memory for programs, variables, and arrays. Multitasking for concurrent execution of up to eight programs
- Home input and forward and reverse limits accepted for every axis
- 8 uncommitted inputs and 8 outputs
- High speed position latch for each axis and output compare
- Expansion for 64 I/O with optional DB-14064 board
- 100-pin SCSI connector. ICM-2900 breaks-out 100-pin cable into screw terminals
- AMP-19540 connects to PCI controller with 100-pin cable and provides four amplifiers for 500 W servos
- Communication drivers for Windows, Mac OSX, and Linux
- CE certified
- Custom hardware and firmware options available

ECONO

PCI Bus Econo Series, 1–4 axes

DMC-18x2 Series

Specifications

System Processor

- Motorola 32-bit microcomputer

Communications Interface

- DMC-18x2: PCI with bi-directional FIFO
- 32-bit PCI interface. 64-bit compatible. 5 V/3.3 V

Commands are sent in ASCII. A binary communication mode is also available as a standard feature

Modes of Motion:

- Point-to-point positioning
- Position Tracking
- Jogging
- 2D Linear and Circular Interpolation with feedrate override
- Linear Interpolation for up to 4 axes
- Tangential Following
- Helical
- Electronic Gearing with multiple masters and ramp-to-gearing
- Gantry Mode
- Electronic Cam
- Contouring
- Teach and playback

Memory

- Program memory size—1000 lines × 80 characters
- 254 variables
- 8000 array elements in up to 30 arrays

Filter

- PID (proportional-integral-derivative) with velocity and acceleration feedforward
- Notch filter and low-pass filter
- Velocity smoothing to minimize jerk
- Integration limits
- Torque limits
- Offset adjustments
- Option for piezo-ceramic motors

Kinematic Ranges

- Position: 32 bit (± 2.15 billion counts per move; automatic rollover; no limit in jog or vector modes)
- Velocity: Up to 12 million counts/sec for servo motors
- Acceleration: Up to 67 million counts/sec²

Uncommitted Digital I/O

	DIGITAL INPUTS	DIGITAL OUTPUTS	ANALOG INPUTS
DMC-18x2	8	8	0

High Speed Position Latch

- Uncommitted inputs 1-4 latch X,Y,Z,W (latches within 0.1 microseconds)

Dedicated Inputs (per axis)

- Main encoder inputs—Channel A, A-, B, B-, I, I- (± 12 V or TTL)
- Forward and reverse limit inputs
- Home input
- Selectable high-speed position latch input
- Selectable abort input for each axis

Dedicated Outputs (per axis)

- Analog motor command output with 16-bit DAC resolution
- Pulse and direction output for step motors
- PWM output also available for servo amplifiers
- Amplifier enable output
- Error output (per card)
- High-speed position compare output (per card)

Minimum Servo Loop Update Time

	STANDARD	-FAST [†]
■ 1–2 axes: 250 μ sec		125 μ sec
■ 3–4 axes: 375 μ sec		250 μ sec

Maximum Encoder Feedback Rate

- 12 MHz

Maximum Stepper Rate

- 3 MHz (Full, half or microstep)

Power Requirements

- DMC-18x2:
  - +5V 750 mA
  - 12V 20 mA
  - +12V 20 mA
  - +3.3V 100 mA*

Environmental

- Operating temperature: 0–70° C
- Humidity: 20–95% RH, non-condensing

Mechanical

- DMC-18x2: 7.275" × 4.2"

Connectors

- 100-pin HD SCSI

* DMC-18x2 revision E and higher require 3.3V from PCI bus.

Order DMC-18x2-3VREG to have a regulator installed to allow 5V only supply.

[†] Reduced feature set for -FAST.

PCI Bus Econo Series, 1–4 axes

DMC-18x2 Series

Connectors

100-pin, high density; Connector: Amp# 2-178238-9,
Cable: Amp# 2-175677-9; Enclosure: Amp# 176793-9

Axis 1–4 DMC-18x2

1 Ground	51 NC
2 Ground	52 Ground
3 5 V	53 5 V
4 Error output*	54 Limit common
5 Reset*	55 Home W
6 Encoder-output compare	56 Reverse limit W
7 Ground	57 Forward limit W
8 Ground	58 Home Z
9 Motor command W	59 Reverse limit Z
10 Sign W / dir W	60 Forward limit Z
11 PWM W / step W	61 Home Y
12 Motor command Z	62 Reverse limit Y
13 Sign Z / dir Z	63 Forward limit Y
14 PWM Z / step Z	64 Home X
15 Motor command Y	65 Reverse limit X
16 Sign Y / dir Y	66 Forward limit X
17 PWM Y / step Y	67 Ground
18 Motor command X	68 5 V
19 Sign X / dir X	69 Input common
20 PWM X / step X	70 Latch X/Input 1
21 Amp enable W	71 Latch Y/Input 2
22 Amp enable Z	72 Latch Z/Input 3
23 Amp enable Y	73 Latch W/Input 4
24 Amp enable X	74 Input 5
25 A+ X	75 Input 6
26 A- X	76 Input 7
27 B+ X	77 Input 8
28 B- X	78 Abort*
29 I+ X	79 Output 1
30 I- X	80 Output 2
31 A+ Y	81 Output 3
32 A- Y	82 Output 4
33 B+ Y	83 Output 5
34 B- Y	84 Output 6
35 I+ Y	85 Output 7
36 I- Y	86 Output 8
37 A+ Z	87 5 V
38 A- Z	88 Ground
39 B+ Z	89 Ground
40 B- Z	90 Ground
41 I+ Z	91 NC
42 I- Z	92 NC
43 A+ W	93 NC
44 A- W	94 NC
45 B+ W	95 NC
46 B- W	96 NC
47 I+ W	97 NC
48 I- W	98 NC
49 +12 V	99 -12 V
50 +12 V	100 -12 V

*Active low

Connectors—AMP-19540

Interconnect with four 500 W servo drives

J1 Power 8-pin AMP Mate-n-lock II

1 Earth	5 Ground
2 +VM (18 V–80 V)	6 Ground
3 +VM (18 V–80 V)	7 Ground
4 +VM (18 V–80 V)	8 Ground

JX1, JY1, JZ1, JW1 Motor Output 4-pin

AMP Mate-n-lock II

1 Earth
2 Motor phase A
3 Motor phase C
4 Motor phase B

J3 I/O 44-pin HI-density Female D-sub

1 PWM/MCMD Z	23 Latch W/Input 4
2 Output 6	24 Latch X/Input 1
3 Output 8	25 PWM/MCMD X
4 Output 5	26 Home X
5 Output 2	27 Home Y
6 Abort*	28 Home Z
7 Input 6	29 Home W
8 Latch Z/Input 3	30 Error Output*
9 SIGN/AEN Y	31 PWM/MCMD W
10 Encoder-output compare	32 5 V
11 Reverse limit X	33 5 V
12 Reverse limit Y	34 Ground
13 Reverse limit Z	35 Ground
14 Reverse limit W	36 Input 8
15 Forward limit W	37 Input 5
16 SIGN/AEN W	38 Latch Y/Input 2
17 SIGN/AEN Z	39 PWM/MCMD Y
18 Output 7	40 SIGN/AEN X
19 Output 4	41 Forward limit X
20 Output 1	42 Forward limit Y
21 Output 3	43 Forward limit Z
22 Input 7	44 Reset*

J4 X-axis 15-pin HI-density Female D-sub

1 I+ X	9 NC
2 B+ X	10 Hall A X
3 A+ X	11 NC
4 NC	12 NC
5 Ground	13 Hall B X
6 I- X	14 Hall C X
7 B- X	15 5 V
8 A- X	

J5 Y-axis 15-pin HI-density

Female D-sub

1 I+ Y	9 NC
2 B+ Y	10 Hall A Y
3 A+ Y	11 NC
4 NC	12 NC
5 Ground	13 Hall B Y
6 I- Y	14 Hall C Y
7 B- Y	15 5 V
8 A- Y	

J6 Z-axis 15-pin HI-density

Female D-sub

1 I+ Z	9 NC
2 B+ Z	10 Hall A Z
3 A+ Z	11 NC
4 NC	12 NC
5 Ground	13 Hall B Z
6 I- Z	14 Hall C Z
7 B- Z	15 5 V
8 A- Z	

J7 W-axis 15-pin HI-density

Female D-sub

1 I+ W	9 NC
2 B+ W	10 Hall A W
3 A+ W	11 NC
4 NC	12 NC
5 Ground	13 Hall B W
6 I- W	14 Hall C W
7 B- W	15 5 V
8 A- W	

AMP-19540

E.2 ICM-2900 Interconnect Module

PCI Bus Econo Series, 1–4 axes

DMC-18x2 Series

Hardware Accessories

ICM-2900 Interconnect Module

The ICM-2900 breaks-out the 100-pin SCSI cable into screw-type terminals. The ICM-2900-FL has flanges which allow standard screw-type mounting. Specify -OPTO for optoisolated outputs. Specify -HAEN for high amp enable and -LAEN for low amp enable.

ICM-2900 Interconnect Module with flange

AMP-19540 Interconnect with Four 500 Watt Servo Drives

Galil's AMP-19540 is a 4-axis amplifier for driving brush or brushless motors up to 500 Watts each. By interfacing directly to Galil's DMC-18x2 PCI bus controllers, it provides a cost-effective controller/drive solution for multi-axis applications. The AMP-19540 contains four transconductance, PWM amplifiers for driving brush or brushless motors. Each amplifier operates at 18 V to 80 V DC, up to 7 Amps continuous, 10 Amps peak. The AMP-19540 gain setting is easily configured with jumpers. The PWM switching frequency is 60 kHz. The AMP-19540 enclosure has dimensions of 6.8" × 8.75" × 1". It interfaces to a PCI bus controller with a single, 100-pin high density SCSI cable. Signals for each axis are brought out through D-type connectors located on the AMP-19540. For applications with less than three axes, the AMP-19520 two-axis model is available. A shunt regulator option is also available. CE certified.

DB-14064 I/O Expansion

The DB-14064 is an optional board which provides 64 additional I/O for the DMC-18x2 controllers. This board mounts directly onto the back of the controller and provides 64 I/O points configurable by the user for inputs or outputs. The I/O is accessible through two 50-pin headers.

Ordering Information

PART NUMBER	DESCRIPTION	QUANTITY 1	QUANTITY 100
DMC-1812	1-axis Econo PCI motor controller	\$ 795	\$ 595
DMC-1822	2-axis Econo PCI motor controller	\$ 895	\$ 665
DMC-1832	3-axis Econo PCI motor controller	\$1045	\$ 725
DMC-1842	4-axis Econo PCI motor controller	\$1195	\$ 795
-3VREG	Option for 3 Volt regulator which allows for 5V only supply from PCI bus	No extra charge	
CABLE-100-1M	100-pin HD cable in 1 meter length	\$ 165	\$ 125
CABLE-100-2M	100-pin HD cable in 2-meter length	\$ 180	\$ 135
CABLE-100-4M	100-pin HD cable in 4 meter length	\$ 195	\$ 145
ICM-2900-FL	Interconnect module (use 1 for every 4 axes). Specify -HAEN for high amp enable or -LAEN for low amp enable. Specify -FL for flange	\$ 295	\$ 195
ICM-2900-OPTO	ICM with optoisolated outputs	\$ 345	\$ 245
AMP-19520	2-axis amplifier for 500 W servo motors	\$ 595	\$ 395
AMP-19540	4-axis amplifier for 500 W servo motors	\$ 795	\$ 495
-SR	Shunt regulator option for AMP-195x0	\$ 50	\$ 25
DB-14064	Attachment board for 64 additional I/O, DMC-18x2	\$ 295	\$ 195
GalilTools-Lite	Editor, Terminal, Watch Tools. Includes communication library for developers-supports C++, VB, C#, LabVIEW and more	Free download	
GalilTools	Above with Scope and Tuner	\$ 195	
ActiveX Tool Kit	Custom ActiveX controls for Microsoft platforms	\$ 595	

Galil offers additional quantity discounts for purchases between 1 and 100. Consult Galil for a quotation.

Appendix F

Advanced Motor Controls (AMC) Analog DC Drives

The datasheet for Advanced Motion Controls (AMC) Analog DC Drive component utilized in this work is listed in this appendix.

Products and System Requirements / Analog Drive Family Overview

Standard and Custom Models The drives in the tables below are the standard product line of *ADVANCED* Motion Controls analog servo drives. Note that not all possible part number combinations from the product family numbering structure (Figure 2.1) are offered as standard drives. Please contact *ADVANCED* Motion Controls Sales Department for further information and details on custom drive solutions.

TABLE 2.1 Brushed $\pm 10V$ Analog DC Drives

Drive Number	VDC (Nominal)	Peak Current (A)	Cont. Current (A)
12A8	20-80	12	8
25A8	20-80	25	12.5
30A8	20-80	30	15
50A8	20-80	50	25
120A10	20-80	120	80
20A20	40-190	20	10
25A20	40-190	25	12.5
50A20	40-190	50	25
100A40	80-400	100	50

TABLE 2.2 Brushless $\pm 10V$ Analog DC Drives

Drive Number	VDC (Nominal)	Peak Current (A)	Cont. Current (A)
B15A8	20-80	15	7.5
BE15A8	20-80	15	7.5
BE15A8-H	20-80	15	7.5
B30A8	20-80	30	15
BE30A8	20-80	30	15
BX30A8	20-80	30	15
B25A20	40-190	25	12.5
BE25A20	40-190	25	12.5
BX25A20	80-200	25	12.5
B40A20	40-190	40	20
BE40A20	40-190	40	20
B30A40	80-400	30	15
B40A40	80-400	40	20

TABLE 2.3 Brushed $\pm 10V$ Analog AC Drives

Drive Number	VAC (Nominal)	Peak Current (A)	Cont. Current (A)
19A20AC	30-125	18	8
30A20AC	30-125	30	15

TABLE 2.4 Brushless $\pm 10V$ Analog AC Drives

Drive Number	VAC (Nominal)	Peak Current (A)	Cont. Current (A)
B25A20AC	30-125	25	12.5
BE25A20AC	30-125	25	12.5
BX25A20AC	45-125	25	12.5
B30A40AC	45-270	30	15
B40A40AC	45-270	40	20

TABLE 2.5 Brushed PWM Input DC Drives

Drive Number	VDC (Nominal)	Peak Current (A)	Cont. Current (A)
30A8DD	20-80	30	15
50A8DD	20-80	50	25
25A20DD	40-190	25	12.5
50A20DD	40-190	50	25

TABLE 2.6 Brushless PWM Input DC Drives

Drive Number	VDC (Nominal)	Peak Current (A)	Cont. Current (A)
B015A8	20-80	15	7.5
B030A8	20-80	30	15
B0C30A8	20-80	30	15
B025A20	40-190	25	12.5
B0C25A20	40-190	25	12.5
B0C40A20	80-190	40	20

TABLE 2.7 Brushless PWM Input AC Drives

Drive Number	VAC (Nominal)	Peak Current (A)	Cont. Current (A)
B025A20AC	30-125	25	12.5

TABLE 2.8 Sinusoidal Input DC Drives

Drive Number	VDC (Nominal)	Peak Current (A)	Cont. Current (A _{max})
B15A8	20-80	18	8
BX30A8	20-80	30	15
B00A8	20-80	80	30
B100A8	20-80	100	50
BX25A20	80-190	25	12.5
B30A40	80-400	30	15
B60A40	80-400	60	30
B100A40	80-400	100	50

TABLE 2.9 Sinusoidal Input AC Supply Drives

Drive Number	VAC (Nominal)	Peak Current (A)	Cont. Current (A _{max})
B30A40AC	45-285	30	15
B60A40AC	45-270	60	30
B100A40AC	45-270	100	50

Appendix G

GalilTools Interface

The GalilTools Interface along with samples of motion programs are shown in Figure D.1 below:

Figure G.1 GalilTools Interface with sample programs

Appendix H

Keyence Laser Displacement Sensor

The datasheets for Keyence laser displacement sensor components i) LK-G3001 All-in-one controller and ii) LK-G402 Laser head are listed in the following subsections.

H.1 LK-G3001 All-in-one controller

SYSTEM

SPECIFICATION

Controller

Type		All-in-one model	Separate monitor model ¹⁾
Model	NPN	LK-G3001V	LK-G3001/LK-GD500
	PNP	LK-G3001PV	LK-G3001P/LK-GD500
Display	Head compatibility	All LK-G sensor heads are compatible	
	Number of connectable sensors	Maximum of 2 units	
	Minimum display unit	0.01 μm 0.0004 mil	
	Display range	±0.999.99 mm to ±0.999.99 μm (Selectable from six levels)	
Refresh rate	Refresh rate	10 times/sec	
	Analog voltage output	±10 V x 2 outputs, output impedance: 100 Ω	
	Analog current output	4 to 20 mA x 2 outputs, maximum load resistance: 350 Ω	
	Timing/Reset/Auto-zero input	For OUT1, non-voltage or voltage input ²⁾	
Terminal block	Laser remote interlock input	Non-voltage input ⁴⁾	
	Comparator output	For OUT1, NPN or PNP open-collector output ²⁾	
	Alarm output	For OUT1, NPN or PNP open-collector output ²⁾ (N.C.)	
	Timing/Reset/Auto-zero input	For OUT2, non-voltage or voltage input ²⁾	
Expansion connector	Program switching input	Non-voltage or voltage input ²⁾ x 3 inputs	
	Laser-Off input	For Head A/Head B, non-voltage or voltage input ⁴⁾	
	Comparator output	For OUT2, NPN or PNP open-collector output ²⁾	
	Alarm output	For OUT2, NPN or PNP open-collector output ²⁾ (N.C.)	
Binary	Binary output	Measured data output (21 bits), OUT1/OUT2 selectable, NPN or PNP open-collector output ²⁾	
	Strobe output	NPN or PNP open-collector output ²⁾	
	Binary selector output	NPN or PNP open-collector output ²⁾	
	Binary selector input	Non-voltage or voltage input ²⁾	
RS-232C interface		Measured data output and control input/output (Maximum baud rate: 115,200 bps, selectable)	
USB interface		In conformity with USB Revision 2.0 Full speed (USB1.1 compatible)	
Major functions		2 OUT simultaneous measurement, Operation, Averaging, Filter, Calibration, Measurement, AUTO ZERO, Sampling frequency setting, Mutual interference prevention, Data storage, 8-program memory, ECO mode, ABLE setting, Target setting, ABLE tuning, Selection of measurement surface of transparent target, Correction of setting support software, Selectable head-mounting, etc.	
Power supply voltage		24 VDC±10%, Ripple: 10% (P to P) or less	
Current consumption		500 mA or less with 1 head/500 mA or less with 2 heads	
Ambient temperature		0 to 30°C, No condensation	
Relative humidity		35 to 85%, No condensation	
Weight		Approx. 440 g (LK-G3001V/LK-G3001PV), Approx. 370 g (LK-G3001P/LK-G3001P), Approx. 60 g (LK-GD500)	

1. LK-G3001(P) can be operated singly. The measured value display and setting modifications can be performed on the display panel (LK-GD500) or via the setting support software (LK-H1W).

2. The rating of the NPN open-collector: 50 mA max. (40 V max.), residual voltage of 0.5 V max. The rating of the PNP open-collector: 50 mA max. (30 V max.), residual voltage of 0.5 V max.

3. (NPN model) The rating of non-voltage input: 1 V or less ON voltage, 0.5 mA or less OFF current. (PNP model) The rating of voltage input: 10.2 V or more ON voltage (28.4 V max.) 0.5 mA or less OFF current.

H.2 LK-G402 Laser Head

SELECTION GUIDE

Sensor Heads

TYPE		MODEL	MEASURING RANGE	REPEATABILITY	SPOT DIAMETER
Super Precision	Small spot	LK-G10	 Measuring range 0.39"±0.04" 10±1 mm	0.0004 Mil 0.01 µm	Ø0.79 Mil Ø20 µm
	Wide beam	LK-G15			0.79x19.89 Mil 20x500 µm
High Accuracy	Small spot	LK-G32	 Measuring range 1.18"±0.2" 30±5 mm	0.002 Mil 0.05 µm	Ø1.18 Mil Ø30 µm
	Wide beam	LK-G37			1.18x33.46 Mil 30x850 µm
Multi-Purpose	Small spot	LK-G82	 Measuring range 3.15"±0.59" 80±15 mm	0.008 Mil 0.2 µm	Ø2.76 Mil Ø70 µm
	Wide beam	LK-G87			2.76x43.31 Mil 70x1100 µm
Long Distance	Small spot	LK-G152	 Measuring range 5.91"±1.57" 150±40 mm	0.02 Mil 0.5 µm	Ø4.72 Mil Ø120 µm
	Wide beam	LK-G157			4.72x66.93 Mil 120x1700 µm
High-speed Long Distance	Small spot	LK-G402	 Measuring range 15.75"±3.94" 400±100 mm	0.08 Mil 2 µm	Ø11.42 Mil Ø290 µm
	Wide beam	LK-G407			11.42x326.8 Mil 290x8300 µm
Ultra Long Distance	Small spot	LK-G502	 Measuring range 19.69"±9.84"±19.69" 500-250/±500 mm	0.08 Mil 2 µm	Ø11.51 Mil Ø300 µm
	Wide beam	LK-G507			11.51x374 Mil 300x9500 µm

Controllers

TYPE	OUTPUT	
	NPN	PNP
ALL-In-one	LK-G3001V	LK-G3001PV
Separate Display	LK-G3001	LK-G3001P

SPECIFICATION

Model		LK-G407/LK-G402		LK-G507/LK-G502	
Mounting mode		Diffused reflection	Specular reflection	Diffused reflection	Specular reflection
Reference distance		15.75" 400 mm	15.67" 398 mm	19.69" 500 mm	19.59" 497.5 mm
Measuring range ¹		3.94" ±100 mm	3.90" ±99 mm	-9.84" to 19.69" ±250 to ±500 mm	-9.80" to 19.51" ±249 to ±498 mm
Light source	Wavelength	Red semiconductor laser			
	Laser Class	650 nm (visible light)			
	Output	Class II (FDA CDRH 21CFR PART1040.10) 0.95 mW			
Spot diameter (at reference distance)		Approx. 11.42 x 526.8 μm 290 x 8900 μm (G407) Approx. ±11.42 Mm ±290 μm (G402)		Approx. 11.81 x 374 μm 300 x 9500 μm (G507) Approx. ±11.8 Mm ±300 μm (G502)	
Linearity ²		±0.05% of F.S. (F.S. = ±3.94" ±100 mm)		±0.05% of F.S. (±0.84 Mm ±250 μm) ^{4a} -9.84" to +9.84" ±250 mm to ±250 mm -high accuracy range- ±0.02% of F.S. (±0.9 Mm ±100 μm) -9.84" to +1.97" ±250 mm to ±50 mm -long range- ±0.1% of F.S. (±10.5 Mm ±500 μm) -9.84" to +19.69" ±250 mm to ±500 mm (F.S. = ±9.84" ±250 mm)	
Repeatability ³		0.08 Mm 2 μm			
Sampling frequency		20/50/100/200/500/1000 μs (Selectable from 6 levels)			
LED display		Near the center of the measurement: Green lights Within the measurement area: Orange lights Outside the measurement area: Orange flashing			
Temperature characteristics		0.01% of F.S./°C (F.S. = ±3.94" ±100 mm)		0.01% of F.S./°C (F.S. = ±9.84" ±250 mm)	
Enclosure rating		IP67 (IEC60529)			
Ambient light		Incandescent lamp or fluorescent lamp: 5000 lux max.			
Ambient temperature		0 to +50°C (32 to 122°F), No condensation			
Relative humidity		35 to 85%, No condensation			
Vibrations		10 to 55 Hz, multiple amplitude 0.08" 1.5 mm; two hours in each direction of X, Y, and Z			
Material		Aluminum die-cast			
Weight (including the cable)		Approx. 380 g			

- The range is obtained by measuring KEYENCE's standard target (ceramic).
 <LK-G407/LK-G402>
 When the sampling rate is 20 μs, the range becomes -2.78" (-70 mm) (NEAR side) to -3.94" (-100 mm) (NEAR side) for diffuse reflection.
 When the sampling rate is 20 μs, the range becomes -2.78" (-70 mm) (NEAR side) to -3.90" (-99 mm) (NEAR side) for specular reflection.
 <LK-G507/LK-G502>
 When the sampling rate is 20 μs, the range becomes -9.84" (-250 mm) (NEAR side) to -9.84" (-250 mm) (NEAR side) for diffuse reflection.
 When the sampling rate is 20 μs, the range becomes -9.84" (-250 mm) (NEAR side) to -9.80" (-249 mm) (NEAR side) for specular reflection.
 When the sampling rate is 50 μs, the range becomes -4.32" (-125 mm) (NEAR side) to -9.84" (-250 mm) (NEAR side) for diffuse reflection.
 When the sampling rate is 50 μs, the range becomes -4.32" (-125 mm) (NEAR side) to -9.80" (-249 mm) (NEAR side) for specular reflection.
 When the sampling rate is 100 μs, the range becomes -4.32" (-125 mm) (NEAR side) to -9.80" (-249 mm) (NEAR side) for specular reflection.
- The range is obtained by measuring KEYENCE's standard target (ceramic) with the Standard mode.
- The range is obtained by measuring KEYENCE's standard (SUS) with 4096 times of averaging at the reference distance.
- All are calculated at F.S. = ±9.84" ±250 mm.
- "High accuracy range" and "long range" refer to the linearity when these ranges are used.

Extension cable [Cable between the head and controller]

Model	LK-GC2	LK-GC5	LK-GC10	LK-GC20	LK-GC30
Cable length	6.6' 2 m	16.4' 5 m	32.8' 10 m	65.6' 20 m	98.4' 30 m
Weight	Approx. 200 g	Approx. 400 g	Approx. 750 g	Approx. 1400 g	Approx. 2000 g

Extension cable [Cable for display panel]

Model	OP-S1654	OP-S1655	OP-S1656
Cable length	0.98' 0.3 m	9.8' 3 m	32.8' 10 m

ND filter

Model	Description
LK-F1 (for LK-G3C, LK-G8C)	Used when the mirror surface is measured at a mirror reflection setup.
LK-F2 (for LK-G15C, LK-G40C, LK-G50C)	Used when the mirror surface is measured at a mirror reflection setup.

CORD

RS-232C communication cable
OP-96368 (2.5m 8.2')

communication cable 9-pin
conversion connector
OP-26401

communication cable 25-pin
conversion connector
OP-96369

Expansion cable 3 m 9.8'
OP-51657

Ethernet cable 3 m 9.8'
OP-66843

LK-G SERIES