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Kinematic Design and Analysis of a 7 Degree-of-Freedom Dual-Stage Inspection Manipulator for Dexterous Subsea Applications

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Abstract. This paper describes the design of a 7 degree-of-freedom (d.o.f) manipulator for underwater inspection applications. The functional requirements of an underwater manipulator for subsea inspection are discussed and the desired performance requirements identified. The inspection process of a weld joint using a manipulator is described and the desirable attributes of a 5 d.o.f manipulator for the inspection process established. A novel kinematic structure, for Underwater Robotic Vehicle (URV) operation, having a 2 d.o.f launching stages and a 5 d.o.f inspection stage is proposed for the manipulator. This configuration increases the dexterity, without compromising on the total reach of the manipulator. The kinematic structure of the 7 d.o.f, 2 stage, manipulator is presented. A hybrid power actuation is proposed for the manipulator to exploit the benefits of both hydraulic as well as electric actuators. Kinematic analysis of the manipulator is presented. The link dimensions of the inspection stage manipulator is done on the basis of kinematic performance indices of the manipulator. The novel kinematic structure and the hybrid power actuation strategy results in a power efficient, dexterous manipulator for underwater applications.

Key words: underwater manipulator, subsea inspection, kinematic design, manipulator dexterity, kinematic/kinetic performance.

1. Introduction

Advancements in Remotely Operated Vehicle (ROV) technology in recent years have resulted in significant enhancements in the inspection and maintenance of underwater structures. Along with the development of ROV technology, the need for special manipulators to perform dexterous underwater operations was also identified. Research and developmental activities in this area has also been receiving renewed interest (Barry et al., 1994; Greig and Broome, 1994; Andrew, 1993). The design of a general-purpose manipulator for submersible applications remains illusive. This is due to the widely differing manipulator requirements between applications. Relevant manipulator parameters include; physical size, envelope configuration, lift capacity, joint mobility, kinematics and actuator type. Special manipulators are designed for particular applications, based on the performance criteria set for the tasks. The inspection of underwater structures is typically performed by

certified divers. They are, typically, deployed to identify damages to the welded joints or flooding of interconnecting members. Non destructive type inspection devices are used in this inspection process. The environment of deployment is generally highly hostile and hazardous. With the advances in underwater robotic vehicles, it is becoming more desirable to replace human divers with automated inspection methods. One of the major challenges in automating the inspection process is in the design of the dexterous manipulator to manipulate within the constrained underwater environment. Design of underwater manipulators is significantly different from the design of factory floor mounted manipulators. Due to the differences in functional requirements of these applications (Greig and Broome, 1994; Andrew, 1993; Andeen, 1988), customised manipulators are highly desirable. In this application the manipulator is mounted onto a robotic vehicle of highly uncertain dynamic characteristics and the manipulators may be required to operate in a highly constrained environments. The size, weight, kinematic structure and folded configurations are significant factors in its effective deployment.

The manipulator, presented, is being developed as an inspection arm of the tele-operated Underwater Robotic Vehicle (URV), being developed at the Robotic Research Centre of the Nanyang Technological University. It is undertaken as part of a research programme on development of technologies and systems for the advancement of knowledge and for possible commercial exploitation relevant to the oil and Gas industry. Under this programme, a compact URV and a unified pilot training and Control system has been developed (Seet et al., 2001). The manipulator is expected to enhance the intervention capabilities of the URV. Figure 1 shows the general scenario of using a manipulator, on board the URV, manipulating a structure in an NDT inspection.

Figure 1. The URV and manipulator in an idealised operation.

2. Functional Requirements of the Inspection Manipulator

The inspection manipulator is responsible for performing all the tasks associated with the inspection process of an underwater weld structure. The process includes; cleaning off the surface growth to expose the weld joint, tracking the weld profile and tracing a probe along the weld seam to perform non-destructive testing of the joint using the industry tested alternating current field measurement technique. The major functional requirements of this manipulator are:

1. It must be able to perform the inspection with the URV docked at a distance (approx. 1 m) away from the inspection point. This will ensure an unobstructed workspace for the manipulator to manipulate in and to avoid obstacles posed by structural members.
2. The manipulation space may be highly constrained. A highly dexterous workspace is required for the manipulator to manipulate within the constrained work environment. It is, typically, desirable to have the dexterous workspace forward of the URV towards the boundary of the actual inspection area.
3. The kinematic structure of the manipulator must allow a fully folded configuration, which ensures minimum disturbance to the URV dynamics during its taxiing to and from work site.
4. The manipulator must be capable of tracking a complete weld joint from one or two docked positions of the URV.
5. The manipulator must be capable of carrying payloads such as cleaning devices, inspection probes and welding equipments.
6. The length of the manipulator in its fully stretched configuration must be 2.0–2.5 m. This has been fixed on the basis of the available information about underwater structures and ROV capabilities (Reddy, 1991; Francis, 1989).

3. Design Constraints

From the functional requirements stated in previous section, it is clear that a manipulator with a long reach and a large dexterous workspace, is the minimum requirement of an inspection manipulator. One of the major constraints in the design of such a manipulator is the compromise between the large workspace requirements and manipulator dexterity. In order to have a large workspace, it is necessary to have large link lengths for the manipulator or to have redundant structures. The dexterity of the manipulator as well as the manipulability will be severely affected due to increased link lengths. This will also lead to an increase in the total weight of the manipulator and an increase in torque requirements.

Another constraint in the manipulator design is the selection of actuators for the joints. Most undersea manipulators are hydraulically powered due to the need for large power to weight ratio and large torque requirements. Hydraulic drives have also been claimed to be more reliable and robust under the conditions of opera-

tion. Hydraulic drives, however, have a number of drawbacks. The most significant drawback is its relatively poor positional accuracy.

Due to the large reach, torque requirements of the actuators at the base end would be extremely large. Hydraulic motors would be an advantage. Having all joints hydraulically actuated would degrade its positional accuracy. Our proposal attempts to address these design issues in the development of the hybrid subsea manipulator.

4. Design of Subsea Inspection Manipulator

The functional requirements and the design constraints explained in the previous section warrants the design of a customised manipulator. Two of the most basic issues in the design of the manipulator are the number of degrees of freedom (d.o.f) and the resulting kinematic structure. The number of degrees-of-freedom required for a manipulator is decided on the basis of the task to be performed by the manipulator. For a general-purpose manipulator, it is quite common to have 6 d.o.f, so as to enable it to reach the desired position and orientation in space. In order to assess the requirement of number of degrees of freedom for the inspection manipulator, it is necessary to study the inspection task and define it as a Cartesian task. In the following section, the inspection of a weld joint using a manipulator is analysed as a Cartesian task.

4.1. INSPECTION OF A WELD JOINT USING A MANIPULATOR AND A PROBE

The fundamental task of the manipulator during an inspection task is to position the inspection probe at the point of inspection and orient it in the desired direction. For the purpose of analysis, we can always assume a weld seam as circular in cross section as shown in Figure 2. During a non-contact inspection process, it is necessary for the inspection tool to follow the weld seam trajectory, with the tool in proper orientation. Assume that the coordinate frame XYZ is attached to the inspection probe as shown in Figure 2. An instantaneous coordinate frame, $X_oY_oZ_o$, is attached to the inspected weld point, in such a way that the Y_o axis is always normal to the weld surface. The axis X_o is tangent to it, and axis Z_o is along the width of the weld joint and the origin at the point of inspection. During a perfect inspection process, the basic requirement is that at any instant of time, the origins of the coordinate frames of the weld joint and the probe should coincide without any rotation. This requires the positioning of the probe in a three-dimensional space and orienting it in three directions. Thus, it can always be considered as a 6-dimensional Cartesian task, with three positioning and 3 orientations in a Cartesian plane, warranting a 6 d.o.f manipulator to do the task.

The ACFM procedure allows a relaxation in the orientation of the probe (Low, 2000) with respect to the joint coordinate frame at least in one direction without affecting the quality of inspection. The experiments conducted using an Alternat-

Figure 2. Coordinate frame of probe and weldseam.

Figure 3. Relaxation of probe orientation during inspection.

ing Current Field Measurement (ACFM) probe for inspection of weld joints have shown that the probe orientation in one direction, say pitch, can be relaxed up to 60° as shown in Figure 3, without affecting the quality of inspection process. (The actual value of relaxation angle depends on the type of probe and the quality requirements set for the inspection task.) This property of the inspection process simplifies the inspection process to a 5 d.o.f problem-3 positioning and two orientations. Thus a manipulator with 3 d.o.f for positioning and 2 d.o.f for orientation can be used as an inspection arm for weld structures, without affecting the inspection quality.

Having established the sufficiency of a 5 d.o.f manipulator for inspection purposes, the feasibility of such a configuration underwater manipulator was analysed. The design requirements of the manipulator specify a total length of 2 m to 2.5 m and a dexterous workspace towards the boundary of the actual workspace. In order to ensure a dexterous workspace, it is necessary to have the wrist links (last two links) as small as possible and have their rotational axis intersect at a common point. If we design with short wrist links length, the lengths of the other three links will need to be large in order to ensure the required total length requirement of the manipulator. Such large link lengths will affect the manipulation adversely and result in many voids in its workspace. In view of this, it is found that, a 5 d.o.f manipulator cannot satisfy the design requirements of the proposed underwater manipulator. Alternate options are available. One of the options at this stage is to add redundant d.o.f to the manipulator in order to reduce the link lengths, thus improving the manipulability. But, for an underwater manipulator, this is not a feasible option, as the increase in the number of joints will eventually lead to increase in weight as well as additional actuators and associated systems. In order to overcome this design constraint, a novel manipulator architecture having a multi-stage actuation is proposed.

4.2. MULTI-STAGE MANIPULATOR

A multi-stage manipulator is having more than one distinct stages of independent actuation. This can be compared with a micro–macro manipulator concept having a large positioning manipulator carrying a small manipulator for fine manipulation. A two-stage, a launching stage and an inspection stage, configuration is proposed for the underwater manipulator. The inspection stage manipulator is responsible for carrying out all manipulation tasks like, cleaning, tracking and inspection. The launching stage will be used, primarily, to position the inspection stage to a close to the target workspace. Using this scheme, it is possible to increase the overall reach of the manipulator without increasing the length of the inspection stage manipulator. As discussed in the previous section, a 5 d.o.f manipulator can adequately be used as the inspection stage manipulator, and the launching can be provided by a 2 d.o.f manipulator. Thus, a 7 d.o.f, 2 stage manipulator can be concluded to satisfy the design criteria for workspace and dexterity.

4.3. KINEMATIC STRUCTURE OF THE MANIPULATOR

Selecting a particular configuration for a manipulator is purely a qualitative aspect of design and no rigorous reasoning is available to prove the validity of selection. The factors affecting the selection of manipulator configuration are its intended task, workspace, positional reachability, controllability of orientation, link interference, speed of actuation, folded configuration, etc. The kinematic structure for the inspection stage and the launching stages are chosen based on the specific

Figure 4. Kinematic structure of the 5 d.o.f inspection stage manipulator.

Figure 5. Kinematic structure of the 7 d.o.f manipulator.

tasks they have to perform. In the case of inspection stage manipulator, different kinematic structures were proposed and analysed for its workspace, singularities, kinematics and folded configurations. A kinematic structure as shown in Figure 4 was found to be the best option. This configuration has three joints with parallel axis of rotation and two joints with intersecting joint axis. The first three joints can position the end effector in a plane ($X-Z$) and orient it in that plane. The fourth joint is used for positioning the end effector in a plane orthogonal to the plane selected by the first three joints and the fifth joint is used for orienting the end effector along its axis of rotation, orthogonal to all other axes of rotation.

The kinematic structure of the first stage manipulator have been selected in such a way that it will enhance the total reachable workspace and allow an appropriate folded configuration for the combined manipulator.

The first joint of the manipulator has been provided with a rotational axis parallel to the fourth joint of the second stage. This will enhance the reach of the inspection stage manipulator through the entire range of this joint. The second joint axis is parallel to the first joint of the inspection stage and this allows the positioning of the second stage in the ($X-Z$) plane. Thus the launching stage manipulator is capable of positioning the inspection stage manipulator in a 3-dimensional space with very close proximity to the task space. The kinematic structure of the combined manipulator is shown in Figure 5. Further details on the kinematic structure

Figure 6. Folded configuration of the manipulator.

and its salient features are provided in (Asokan et al. 2002, 2001a). Appropriate selection of joint axes for both the stages, allows a perfectly folded configuration for the combined manipulator as shown in Figure 6. Such a configuration ensures minimum influence on the dynamics of the URV during its free flight from one point to another.

4.4. HYBRID POWER STRUCTURE FOR THE MANIPULATOR

As explained in Section 3, the accuracy and manipulation capabilities of the manipulator depends on the type of actuators used for actuating the joints. In order to reap the benefits of both the hydraulic as well as electric actuators, a hybrid power structure has been adopted for the subsea manipulator. Since the inspection stage manipulator requires high positional accuracy, electrical actuators have been selected for this stage. Harmonic drive motors with good torque to weight ratio have been selected. These drives are expected to give good positional accuracy, as the load on the actuators is relatively low due to the small link lengths and payload. High torque hydraulic actuators have been selected to drive the first stage manipulator. Large torque and low positioning accuracy requirements of the launching stage necessitates the use of high torque hydraulic actuators for this stage. Such a hybrid power structure is expected to be highly effective in the deployment of manipulator for inspection tasks.

5. Kinematic Analysis

The geometry of arm motion and the spatial configuration of the manipulator, as a function of time, are analysed in this section. The direct and inverse kinematic problems, link dimensioning, workspace analysis, etc. of the 7 d.o.f manipulator are addressed in the following sections.

5.1. DIRECT KINEMATICS

Direct kinematics of the manipulator can be analysed by adopting the classical Denavit–Hartenberg (1955) convention. Coordinate frames, as shown in Figure 7,

Figure 7. Assignment of coordinate frames.

Table I. DH parameters

Joint	θ	α	a	d
1	θ_1	$\pi/2$	a_1	d_1
2	θ_2	0	a_2	0
3	θ_3	0	a_3	0
4	θ_4	0	a_4	0
5	θ_5	$-\pi/2$	a_5	0
6	θ_6	$\pi/2$	0	0
7	θ_7	0	0	d_7

are assigned to the manipulator joints and the DH parameters of the manipulator are determined as given in Table I.

Homogeneous transformation matrices expressing relative position and orientation between consecutive links are computed and the resulting direct kinematics equation can be expressed in the form

$$T(\theta) = \begin{bmatrix} \mathbf{n}(\theta) & \mathbf{s}(\theta) & \mathbf{a}(\theta) & \mathbf{p}(\theta) \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (1)$$

where θ is the (7×1) vector of joint variables, and $\mathbf{n}$, $\mathbf{s}$, $\mathbf{a}$ are the unit vectors of the end-effector frame and $\mathbf{p}$ is the position vector of the origin of such frame with respect to the origin of the base frame.

5.2. INVERSE KINEMATICS

The inverse kinematics of the manipulator is solved in two stages. In the first stage, the joint angle θ_1 and θ_2 for the launching stage is solved using the position vector $\mathbf{p}(\theta)$ and orientation vector $\mathbf{a}(\theta)$. The second stage solution consists of solving for the joint angles θ_3 to θ_7 for the inspection stage manipulator with θ_1 and θ_2 as known parameters. Since the second stage manipulator has three adjacent joint axes

parallel, a closed form solution can be easily found out. The closed form solution procedure for the manipulator can be found in (Asokan et al., 2001b).

6. Link Dimensioning of the Manipulator

Estimation of the link lengths for the manipulator is one of the critical aspects of the manipulator design. In the design of a multi degree-of-freedom mechanism, selection of proper parameters is often confusing and bound by many constraints like operational workspace, singularity avoidance, dexterity of workspace, etc. (Ceccarelli, 1995; Vijaykumar et al., 1986). For the underwater manipulator described in this paper, the frequently, it is the experience and intuition of the designer, which helps in choosing the parameters. In the case of the manipulator discussed here, optimum link lengths were calculated based on the following criteria: minimum coupling between the links, maximum mobility for the links, and maximum motion efficiency for the links. The strategy adopted to achieve this is explained in the following sections.

6.1. LINK LENGTHS FOR LAUNCHING STAGE

The link parameters for the first stage are selected, based on the requirement of maximum reach of manipulator and the existence of a suitable folded configuration as shown in Figure 6. The kinematic performance of the second stage is largely independent of the first stage and hence, the kinematic/kinetic performance of the first stage has not been considered in the selection of link parameters.

6.2. LINK LENGTHS FOR INSPECTION STAGE

The second stage manipulator has three joints with parallel axes of rotation. The remaining two joints form the wrist of the manipulator. The first three links of the second stage are responsible for positioning the end effector to the required task plane and orienting it. The wrist joints are responsible for positioning and orienting in the other planes and have less influence on the kinematic/kinetic performance of the manipulator. In view of this, the first three links of the second stage manipulator is only considered for dimensioning here.

The optimum link ratios are arrived on the basis of kinematic/kinetic performance indices reported by Lee et al. (1993, 1994). These indices, developed as a means of representing the kinematic/kinetic performance of multi degree of freedom mechanisms, are efficient analytical tools in the synthesis of mechanisms. Local Kinematic Coupling Index (*LKCI*), Local Mobility Index (*LMI*) and Local Efficiency Index (*LEI*) are the three major indices used here for the synthesis of the manipulator. They represent the performance characteristics of the manipulator quantitatively, and were optimised to arrive at the best link lengths ratios for the first three links of the second stage manipulator.

Figure 8. Link parameters of the inspection stage.

The structure of the first three links of the second stage manipulator is shown in Figure 8 along with its DH parameters.

The relation between the joint variables $\theta_3, \theta_4, \theta_5$ and the task space position vector $[\mathbf{XZ}]^T$ for the 3 d.o.f structure is given by Equation (2) as:

$$\begin{bmatrix} \mathbf{X} \\ \mathbf{Z} \end{bmatrix} = \begin{bmatrix} a_3 C_3 + a_4 C_{34} + a_5 C_{345} & a_4 C_{34} + a_5 C_{345} & a_5 C_{345} \\ a_3 S_3 + a_4 S_{34} + a_5 S_{345} & a_4 S_{34} + a_5 S_{345} & a_5 S_{345} \end{bmatrix}, \quad (2)$$

where $C_{ij\dots} = \cos(\theta_i + \theta_j + \dots)$, $S_{ij\dots} = \sin(\theta_i + \theta_j + \dots)$.

Equation (3) gives the Jacobian J , for the above transformation.

$$J = \begin{bmatrix} -a_3 S_3 - a_4 S_{34} - a_5 S_{345} & -a_4 S_{34} - a_5 S_{345} & -a_5 S_{345} \\ a_3 C_3 + a_4 C_{34} + a_5 C_{345} & a_4 C_{34} + a_5 C_{345} & a_5 C_{345} \end{bmatrix}. \quad (3)$$

This Jacobian will be used for the further analysis of the manipulator.

6.3. LOCAL KINEMATIC COUPLING INDEX ($LKCI$)

The cross coupling between two joint motions has been interpreted as a degree of linear dependency between column vectors of the Jacobian matrix and the quantitative measure of this dependency. The Local Kinematic Cross-Coupling Index ($LKCI$) is given as

$$LKCI = \sin(\beta_{ij}), \quad (4)$$

where β_{ij} is the angle of intersection between i th and j th column vectors of J , i.e. V_i and V_j . Then

$$\beta_{ij} = \cos^{-1} \left[\frac{V_i \cdot V_j}{|V_i| \cdot |V_j|} \right]. \quad (5)$$

It can be seen from the above equation that the $LKCI$ is in the range of 0 to 1. In the case when $LKCI = 1$, the column vectors are nearly independent and the joint

motions are completely decoupled. When $LKCI$ is zero, it represents a singular point, where the joint motion is completely coupled.

6.4. COUPLING BETWEEN 4TH AND 5TH LINK

The kinematic coupling between the 4th and 5th links ($LKCI_{45}$) of the manipulator can be analysed using the principle explained above.

$$LKCI_{45} = \sin \left[\cos^{-1} \left[\frac{V_2 \cdot V_3}{|V_2| \cdot |V_3|} \right] \right] \quad (6)$$

$$= \frac{\sqrt{1 - \cos(\theta_5)^2}}{\sqrt{1 + \alpha_2^2 + 2\alpha_2 \cdot \cos(\theta_5)}} \quad (7)$$

where $\alpha_2 = a_5/a_4$.

It is observed from Equations (6) and (7) that the coupling index between 4th and 5th link is independent of θ_4 and is a function of θ_5 and α_2 . The variation of coupling index with respect to θ_5 for its operating range $-2\pi/3$ to $3\pi/4$ is plotted in Figure 9 for different values of α_2 . It was found that the coupling index is zero when $\theta_5 = 0$ for all values of α_2 , and increases with the increase in θ_5 and reaches a maximum value of 1 and then decreases. This trend is common for all values of α_2 . However, for any constant value of θ_5 , the coupling index decreases with the link length ratio as shown (dotted line) in Figure 9. The point at which the coupling index reaches the maximum ($LKCI = 1$, best-conditioned point) varies with the link length ratio and the joint angle. From Equation (6), this point can be derived as:

$$\frac{\sqrt{1 - \cos(\theta_5)^2}}{\sqrt{1 + \alpha_2^2 + 2\alpha_2 \cdot \cos(\theta_5)}} = 1 \quad (8)$$

$$\implies 1 - (\cos(\theta_5))^2 = 1 + \alpha_2^2 + 2\alpha_2 \cdot \cos(\theta_5) \quad (9)$$

$$\implies \cos(\theta_5) = -\alpha_2 \implies \theta_5 = \text{atan2}(\sin(\theta_5), \cos(\theta_5)), \quad (10)$$

where $\alpha_2 = a_5/a_4$.

Figure 9. Variation of coupling index $LKCI_{45}$.

Figure 10. Coupling index $LKCI_{45} = 1$.

Equation (8) gives the value of θ_5 at the best conditioned point for any value of θ_4 and α_2 . Figure 10 shows the variation of θ_5 and α_2 for the best-conditioned point ($LKCI_{45} = 1$). If the value of θ_5 and α_2 is within the working area shown as hatched area in Figure 10, then the best conditioned point will be within the operational workspace of the manipulator. It is observed from the results that, in order to achieve this, the link ratio α_2 is to be kept within 0.6.

6.5. COUPLING INDEX BETWEEN 3RD AND 4TH LINK ($LKCI_{34}$)

The cross coupling index between the 3rd and 4th link is given as:

$$LKCI_{34} = \sin \left[\cos^{-1} \left[\frac{V_1 \cdot V_2}{|V_1| \cdot |V_2|} \right] \right] \quad (11)$$

$$= \sqrt{1 - \left[\frac{1 + \alpha_2^2 + 2\alpha_2 C_5 + (\alpha_2/\alpha_1)C_{45} + (1/\alpha_1)C_4}{\sqrt{X \cdot Y}} \right]^2}, \quad (12)$$

where $X = 1 + \alpha_2^2 + 2\alpha_2 C_5 + 2(\alpha_2/\alpha_1)C_{45} + (1/\alpha_1)^2 + (2/\alpha_1)C_4$, $Y = 1 + \alpha_2^2 + 2\alpha_2 C_5$ and $\alpha_2 = a_5/a_4$.

It can be observed, from the above equation, that the coupling index is a function of α_2 , α_1 , θ_4 and θ_5 and is independent of θ_3 . It was, also, observed that the coupling index increases with the joint angles θ_4 and θ_5 for low values of θ_4 , and also with the link length ratio α_2 (Asokan and Seet, 2001). The point at which the coupling index is maximum ($LKCI_{34} = 1$) can be calculated from Equation (12) by equating it to 1. The joint angle θ_4 at which the $LKCI$ is maximum, can be obtained from Equation (12) as (proof is provided in Appendix A)

$$\theta_4 = \text{atan2}(K, -(K + 1)) + \text{atan2} \left[\pm \sqrt{K^2 + (K + 1)^2 + [\alpha_1 L]^2 + \alpha_1(L)}, \right] \quad (13)$$

where $K = \alpha_2 C_5$ and $L = 1 + \alpha_2^2 + 2K$.

Figure 11. Coupling index $LKCI_{34} = 1, LKCI_{45} = 1$.

Equations (13) and (11) give the joint angles for which the coupling index is 1. By substituting the value of α_2 in terms of θ_5 from Equation (8) into Equation (10) and plotting the values of θ_4 and θ_5 for various values α_1 , we can find out the region where both $LKCI_{34}$ and $LKCI_{45}$ are equal to 1. Figure 11 shows this region within the operational range of joint 4 and 5. From this, it can be observed that both the coupling indices can be kept within the operational range of the links for the link ratios $\alpha_1 < 1$ and $\alpha_2 < 0.6$.

6.6. LOCAL MOBILITY INDEX (*LMI*)

The Local Mobility Index (*LMI*) is a measure of local force manipulability of a mechanism. It is known that the propagation of input joint torque to the end effector force is directly proportional to the Eigen values of generalised Jacobian matrix J_g ($J_g = J \cdot J^T$). *LMI* has been defined as the ratio of the minimum and maximum eigenvalues of J_g .

$$LMI = \frac{\lambda_{\min, J_g}}{\lambda_{\max, J_g}} \equiv \frac{1}{k_{J_g}}, \quad (14)$$

where k_{J_g} is the condition number (Angeles, 1997) of J_g .

For the second stage manipulator, the Jacobian matrix is given by Equation (2). The generalised Jacobian J_g can be obtained as

$$J_g = J \cdot J^T. \quad (15)$$

The *LMI* for the three-link mechanism was calculated by numerical method for various values of joint angles as well as link length ratios. The variation of *LMI* with respect to α_2 and joint angle were analysed and found for all values of α_2 and θ . *LMI* was maximum when θ_5 is within $\pi/4$ to $3\pi/4$ (Asokan and Seet, 2001). This shows that the mechanism has best manipulability in this region. Figure 12 gives a clearer picture about the influence of link ratio on *LMI*. As the link ratios

Figure 12. Variation of LMI with respect to α_1 and α_2 ($\theta_4 = \theta_5 = \pi/2$).

increases, the motion index increases first and then decreases, giving a maximum value in the region, where $0.6 < \alpha_2 < 0.8$ and $0.7 < \alpha_1 < 0.9$.

6.7. LOCAL EFFICIENCY INDEX (LEI)

Local efficiency index is a measure of the motion efficiency of a mechanism. When a robot manipulator is near a singular point, the joint efforts required to attain end point motion in certain directions may be very high or exceed the capability of joint actuators. In contrast, the further the mechanism is away from its singular configuration, the easier the mechanism can arbitrarily change the position and orientation of the mechanism end effector. Thus, the motion efficiency of a mechanism can be considered to be the effort each joint has to generate to obtain the same endpoint output motion. The scalar measure used to define this efficiency is known as local motion efficiency index and is given as the product of the eigenvalues of the generalised Jacobian J_g .

$$LEI = \lambda_1 \lambda_2 \lambda_3 \cdots \lambda_n \cong \det(J_g). \quad (16)$$

Using eigenvalues of the generalised Jacobian, LEI was calculated for different values of joint angles and link ratios. From the results it was observed that the efficiency index increases with the link length ratio (Asokan and Seet, 2001). This is due to the increase in link lengths and consequent increase in distance from the singular point to the joint. However, with the variations in joint angles, the efficiency index varies depending on the position of the joint from the singular point. At singular points efficiency index is zero. Figure 13 shows the variation of LEI with respect to link ratios α_1 and α_2 . It can be observed that, for low values of link ratios, LEI is close to zero, which shows low motion efficiency of the links. As the ratios increase, the mobility also increases. This plot can also be used as a standard chart to fix the link length ratios, based on the motion efficiency requirements of the manipulator.

Figure 13. Variation of LEI with respect to α_1 and α_2 ($\theta_4 = \theta_5 = \pi/2$).

Table II. Joint angle limits and link lengths

Link No.	Joint	Limits (deg)	a (mm)	d (mm)	Length (mm)
1	Rotary	± 90	66	150	–
2	Rotary	$-90-(+135)$	700	0	700
3	Rotary	$-120-(+135)$	490	0	490
4	Rotary	$-120-(+135)$	294	0	294
5	Rotary	$-120-(+135)$	200	0	200
6	Rotary	$-60-(+60)$	0	0	175
7	Rotary	$-180-(+180)$	0	300	125

From the above analysis the following conclusions can be made.

In order to have the best-conditioned point (lowest coupling between links) within the joint space of the manipulator, $\alpha_2 > 0.6$.

For maximum motion efficiency, $0.8 < \alpha_2 < 0.6$ and $0.9 < \alpha_1 < 0.7$.

The higher the link length ratio, the more will be the motion efficiency. However, higher ratios will lead to more variations in efficiency index within the joint space. Therefore, for best results, α_2 should be in the range of 0.4 to 0.7.

Based on the above, the link ratios $\alpha_2 = 0.6$ and $\alpha_1 = 0.7$ have been selected for the manipulator. The link lengths are calculated accordingly and the calculated values are shown in Table II. The variation of kinematic/kinetic indices within the joint ranges for the chosen link lengths are plotted in Figure 14. These plots can be used for the positioning of the URV with respect to a known target point.

7. Joint Angle Limits and Work Space

The operational limits of the joints have been fixed on the basis of the functional requirements as well as mechanical constraints. The joint angle limits for all the

Figure 14. Performance indices.

Figure 15. Manipulator workspace.

joints and the link lengths are given in Table II. The operational workspace of the manipulator can be considered as a union of the workspaces of the launching stage and the inspection stage. The workspace of the inspection stage will be circular in cross section in the (X-Z) plane. The total workspace can be obtained by rotating this subspace through the limits of joint angle 2 in the (X-Z) plane and that of joint angle 1 in the (Y-Z) plane, as shown in Figure 15.

8. Discussion and Conclusion

A three-dimensional model of the manipulator was developed using Pro-Engineer and ported to a simulation package developed with Sense 8 – WorldToolKit graphics toolkit. The kinematic modules were coded in the C language. Forward and inverse kinematic simulation of the manipulator was conducted to test deployment sequences and the efficacy of the design. The simulations were also useful to path planning and optimisation of link motions.

Overcoming the design constraints of a subsea manipulator through alternate design strategies have been described in this paper. The design of the multi-stage manipulator with hybrid actuation strategy is expected to reduce the positional inaccuracies of the manipulator during an inspection task. However, this is yet to be established through practical experiments using the manipulator. Mechanical design and fabrication of the manipulator and its controllers are under progress at the Robotic Research Centre. Further research on enhancing the manipulator capabilities, optimum path planning, etc. are under active research.

Appendix A. Maximum Coupling between 3rd and 4th Link

The cross coupling index between 3rd and 4th link of the manipulator is given by Equation (9). The position at which the index attains the maximum value of 1 is obtained by equating this relation to unity and solving for the variables as a function of joint angle θ_4 as shown below:

$$\sqrt{1 - \left[\frac{1 + \alpha_2^2 + 2\alpha_2 C_5 + (\alpha_2/\alpha_1)C_{45} + (1/\alpha_1)C_4}{\sqrt{X \cdot Y}} \right]^2} = 1, \quad (\text{A.1})$$

where $X = 1 + \alpha_2^2 + 2\alpha_2 C_5 + 2(\alpha_2/\alpha_1)C_{45} + (1/\alpha_1)^2 + (2/\alpha_1)C_4$, $Y = 1 + \alpha_2^2 + 2\alpha_2 C_5$ and $\alpha_2 = a_5/a_4$.

Solving the above equation, we get

$$1 + \alpha_2^2 + 2\alpha_2 C_5 + (\alpha_2/\alpha_1)C_{45} + (1/\alpha_1)C_4 = 0, \quad (\text{A.2})$$

thus,

$$1 + \alpha_2^2 + 2\alpha_2 C_5 + (\alpha_2/\alpha_1)C_{45} + (1/\alpha_1)C_4 = 0. \quad (\text{A.3})$$

This can be written as

$$\alpha_1(1 + \alpha_2^2 + 2\alpha_2 C_5) = \alpha_2 C_{45} + C_4. \quad (\text{A.4})$$

By expanding the term C_{45} , we get

$$\alpha_1(1 + \alpha_2^2 + 2\alpha_2 C_5) = S_4(\alpha_2 C_5) - C_4(\alpha_2 C_5 + 1). \quad (\text{A.5})$$

For a constant value of C_5 , Equation (A.5) is in the form of $A \sin(\theta) + B \cos(\theta) = C$, the solution for which is $\theta = \text{atan2}(A, B) + \text{atan2}(\pm \sqrt{A^2 + B^2 - C^2}, C)$. Substituting for the values of A, B, C from Equation (A.5), expression for θ_4 is obtained as shown in Equation (13).

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