OPTIMAL DESIGN OF AN EXOSKELETON HIP USING THREE-DEGREES-OF-FREEDOM SPHERICAL MECHANISM

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Abstract— In this paper, the design of a hip joint of an exoskeleton is presented so as to automatically assist the hip joint motion of a physically weak person. A spherical three-degrees-of-freedom parallel mechanism is used for the purpose. The problem is framed as an optimization problem with an objective of determining the proper connection points for the links of the structure at the human body, keeping in account the aspects of self-collision, human anatomy and comfort. The design parameters are optimized for a specific pose and the workspace around this central configuration is built to develop enough mobility required for the human body to attain different postures.

I. Introduction

Recent progress in the robotic technologies brings a lot of benefits not only in industries, but also in amusement, welfare and medicine. Research in the process of rehabilitation is of vital interest and there lies the development of *exoskeletons*. Development task of first practical models of human exoskeletons have been taken up by some companies and research centres in recent years [1, 2]. This paper proposes the design of a hip joint of a human exoskeleton to automatically assist the hip joint motion of a physically weak person such as elderly, disabled or injured one. The task is not smooth because the goal here is not just to develop a working mechanism. As this mechanical structure is to be carried by a human body, it needs to fulfill a couple of factors. First, it should be light in weight. Secondly, the location of the connection points and the shape of the links should not cause discomfort to the person in any of the postures. This complexity of mechanical structure is one of the reasons why very few researchers have worked on exoskeletons, even though there are many interesting applications. One such structure was designed and presented by Kondak et al [3], based on the Stewart platform. Although the design shows good performance, it requires six actuators for the purpose, thus implying higher cost and weight. Since all 6-dofs are not needed for the actual purpose, working out an alternative with lesser degrees of freedom is surely worth paying attention. In the present design, we use a sophisticated three-actuator spherical structure to acquire all necessary movements for a human hip joint.

The rotational mechanism used is a member of a class of spherical mechanisms in which all axes intersect at a point located at the centre of the mechanism. As the human hip joint can be approximated by a spherical (ball and socket) joint, locating the rotational centre of the spherical mechanism at the hip joint makes it suitable to represent the hip joint motion. The mechanism used consists of three structurally identical kinematic sub-chains connecting the base of the structure to the common platform, as shown in Fig. 1. On each chain, there is one actuated revolute joint and two passive revolute joints. The three motors of the manipulator are fixed at the base. This can be viewed as representing waist of the person as the base of the mechanism and the thigh playing the role of the platform. So, three actuators (one at the base joint of each chain) would supply moments needed to keep the platform (human thigh) in the required orientation.

The design problem of the mechanism has been framed as an optimization problem of determining the fixed geometric parameters, keeping in account the constraints over these design parameters. For optimizing the mechanism structure, the kinematic equations and Jacobian matrix are derived. The kinematic analysis of the spherical mechanism has been addressed earlier by many researchers [4-7], but these references have used a few symmetric features in the mechanism. No such assumption on symmetric architecture has been used in this paper as that restricts the choices for synthesis of the manipulator. Derivation of kinematic equations, similar to one given in Gosselin et al [4], for the general spherical manipulator is carried out. The condition of the Jacobian matrix of the manipulator is taken as the performance metric for the design purpose [3, 8-

10]. The parameters are optimized for a specific configuration and then the workspace around this central configuration is examined. The results of this workspace analysis portray the success of the design by showing enough mobility for the human hip.

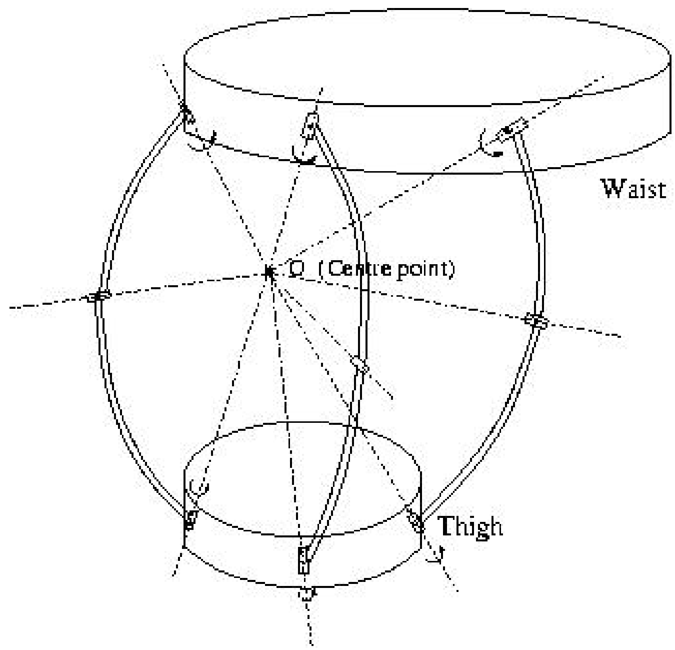

Figure 1: Schematic of 3-DOF parallel mechanism for an exoskeleton hip

In the next section, the kinematic equations for the mechanism are developed. The section also includes the Jacobian calculations. In section III, the formulation of the optimization problem is presented along with the discussion of its solution. Section IV is devoted to workspace analysis around the central configuration and finally, in the last section, contributions of the present work are summarized.

II. Manipulator Kinematics

A. Spherical mechanism – conventions and notations

The mechanism under study is a spherical mechanism in which rotary axes of all the links intersect at a single point located at the centre of the mechanism. The three structurally identical chains of the mechanism, connecting the waist of the human body to the thigh, have one actuator and two passive joints each. The three actuators are fixed at the base of the mechanism. The point of concurrency, O of all axes is located at the hip joint of the human body. All the links of the spherical manipulator move on a sphere with centre at O. This point is taken as the origin of all the reference frames of the mechanism which provides pure rotation of each frame with respect to another.

For the frame assignments and definition of the axes, suffix 'i' represents the corresponding chain with $i = 1,2,3$. R_0, with axes x_0, y_0, z_0, is taken as the base reference frame, as shown in Fig. 2. A frame is assigned to each link in such a way that z-axis is directed along the joint axis. For the frame attached to each of the base links, the x-axis is taken as orthogonal to the corresponding actuator axis and to z_0. The link angle α_{ij} expresses the angle between the $j-th$ and $(j+1)-th$ axis for each leg, for $j = 1,2$. These are fixed parameters to be defined as part of the mechanism geometry. The actuator angles θ_i denote the rotation of actuator links about motor axes. Using these, the frames associated to the intermediate joints for each leg are defined by following the Denavit-Hartenberg (DH) conventions

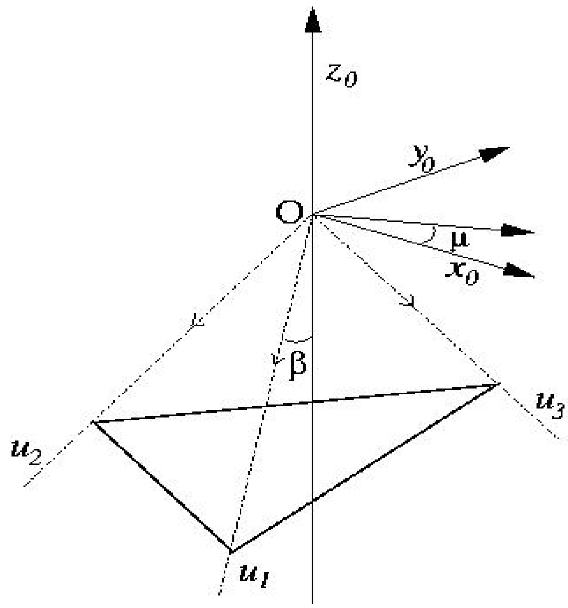

Figure 2: Geometry of the base link

.**B. Kinematic equations of mechanism**

Kinematic analysis of spherical 3-dof manipulator has been studied by a few authors to a great extent, but these references have presented the formulations based on certain assumptions in its architecture. This helps in reducing the level of complexity but with a loss of generality. A spherical mechanism investigated by Gosselin [8], though general comparatively, has also used an assumption of symmetric legs (chains). The kinematic equations worked out and used in this paper are free from any such assumption, although similar in steps of development. This provides a larger search space for synthesis.

The representation of u_i, the unit vector along the $i-th$ actuator axis, in R_0 is given by

$$u_i = R_i(\beta_{1i}, \mu_{1i})\ e_3, \tag{1}$$

where, R_i is the rotation matrix representing the orientation of the frame associated to actuated joint of leg i with respect to the base frame, for $i = 1,2,3$. It is defined by using angles β_{1i} and μ_{1i}, that u_i makes with negative of z_0 and the x-axis of the actuator frame makes with x_0, respectively, and is given by

$$R_i = \begin{pmatrix} \cos\mu_{1i} & \sin\mu_{1i}\cos\beta_{1i} & \sin\mu_{1i}\sin\beta_{1i} \\ \sin\mu_{1i} & -\cos\mu_{1i}\cos\beta_{1i} & -\cos\mu_{1i}\sin\beta_{1i} \\ 0 & \sin\beta_{1i} & -\cos\beta_{1i} \end{pmatrix}.$$

Using the DH notation for the DH parameters α_{ij} and θ_i for each leg i, the intermediate axes w_i are computed as

$$w_i = \begin{pmatrix} -\sin\theta_i & -\cos\alpha_{i1}\cos\theta_i & \sin\alpha_{i1}\cos\theta_i \\ \cos\theta_i & -\cos\alpha_{i1}\sin\theta_i & \sin\alpha_{i1}\sin\theta_i \\ 0 & \sin\alpha_{i1} & \cos\alpha_{i1} \end{pmatrix} u_i \tag{2}$$

and hence, the expression of w_i in frame R_0 is given by

$$w_i = \begin{bmatrix} \cos\mu_{1i}\sin\alpha_{i1}\cos\theta_i + \sin\mu_{1i}\cos\beta_{1i}\sin\alpha_{i1}\sin\theta_i + \sin\mu_{1i}\sin\beta_{1i}\cos\alpha_{i1} \\ \sin\mu_{1i}\sin\alpha_{i1}\cos\theta_i - \cos\mu_{1i}\cos\beta_{1i}\sin\alpha_{i1}\sin\theta_i - \cos\mu_{1i}\sin\beta_{1i}\cos\alpha_{i1} \\ \sin\beta_{1i}\sin\alpha_{i1}\sin\theta_i - \cos\beta_{1i}\cos\alpha_{i1} \end{bmatrix}. \tag{3}$$

To define v_i , the unit vector along the end-effector axis of each leg, we use a frame of reference R_g which has a fixed orientation[1] with respect to the base frame, specified by R_{init} as

$$R_{init} = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}.$$

Thus, with β_{2i} and μ_{2i} as the angles defining end-effector axes corresponding to the two defining actuator axes, v_i with respect to R_g is given by

$$v_i = R_i(\beta_{2i}, \mu_{2i})\ e_3\ . \tag{4}$$

To express v_i in base frame we define ϕ_1 , ϕ_2 , ϕ_3 as the roll, pitch, yaw angles, respectively and obtain

$$v_i = \begin{bmatrix} c_3c_2 \sin\mu_{2i} \sin\beta_{2i} + (c_3s_2s_1 - s_3c_1)\cos\mu_{2i}\cos\beta_{2i} + (c_3s_2c_1 + s_3s_1)\cos\beta_{2i} \\ s_3c_2 \sin\mu_{2i} \sin\beta_{2i} - (s_3s_2s_1 + c_3c_1)\cos\mu_{2i}\cos\beta_{2i} - (s_3s_2c_1 - c_3s_1)\cos\beta_{2i} \\ s_2 \sin\mu_{2i} \sin\beta_{2i} + c_2s_1 \cos\mu_{2i} \sin\beta_{2i} + c_2c_1\cos\beta_{2i} \end{bmatrix}. \tag{5}$$

where c_i and s_i denote the cosine and sine of ϕ_i , respectively, for $i = 1,2,3$.
The relation between w_i and v_i presents the kinematic equations for the manipulator as

$$w_i . v_i = \cos\alpha_{2i}\ ,\ \forall i = 1,2,3. \tag{6}$$

C. Jacobian matrix

The Jacobian matrix of spherical mechanism relates the joint velocities of the manipulator to the end-effector velocities. In serial manipulators the relation is expressed by the equation $\omega = J\dot{\theta}$ with J as the Jacobian matrix. On the other hand, in parallel actuated manipulators, the mapping is expressed in reverse order and is defined as $\dot{\theta} = J\omega$. The Jacobian matrix of a spherical mechanism, as presented in [3], is given by

$$J = B^{-1}A \tag{7}$$

where

$$A^T = \left[\left(w_1 \times v_1\right) \quad \left(w_2 \times v_2\right) \quad \left(w_3 \times v_3\right) \right],$$
$$B = diag\left[c_1, c_2, c_3\right] \text{ with } c_i = \left(u_i \times w_i\right).v_i$$

for each leg i . This expression for the Jacobian matrix has been used to characterize the kinematic accuracy of the manipulator in the next section.

III. Mechanism Optimization

A. Optimization problem formulation

The goal of the design problem of this paper is to determine the locations of the points connecting the links of the spherical mechanism to the frame worn by the human body, taking into consideration the constraints on the design parameters to avoid self-collisions and to be around the human body measurements. This problem can be defined and solved as an optimization problem. To proceed for that, we choose a *mean configuration*[2] for which the mechanism will be optimized and the solution

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[1] To have better intuitive feel and to represent the end-effector axes similar to actuator axes

[2] A configuration here is meant by posture of the human body and defined by the required orientation of the platform (thigh) frame with respect to the base (waist) frame.

will then be used for the analysis of the mechanism for different configurations around this central one. For the purpose, we select values for ϕ_1, ϕ_2, ϕ_3 as $0, \left(-\frac{\pi}{4}\right), 0$ respectively, to represent the mean configuration. This is the estimated mean position of the predicted workspace.

To formulate the optimization problem, the first step is to select the objective function. An important consideration in the manipulator design is its dexterity that signifies how easily and accurately the object can be manipulated. As the focus of this paper is towards kinematics of the mechanism, the Jacobian of the manipulator serves well to characterize the measure of dexterity. Therefore, the condition number[3] of the Jacobian matrix, given in Eqn. 7, is taken as the objective of the design problem. In this paper, the condition number is computed as $\kappa(J) = \| J \| \, \| J^{-1} \|$, where $\| . \|$ denotes the norm of the matrix argument and taken as Euclidean norm given by $\| J \| = \sqrt{\mathrm{Trace}(JWJ^T)}$ with $W = \mathrm{diag}\left(\frac{1}{\mathrm{n}}, \frac{1}{\mathrm{n}}, \ldots, \frac{1}{\mathrm{n}}\right)$, for n number of rows of the matrix J.

To remain in the limits of human anatomy and taking into account the comfort of the person in different postures we need to apply a few constraints on the problem. Besides, the kinematic equations, derived in the previous section, are to be satisfied by the design parameters along with the mean configuration. For the later, we consider kinematic equations as the (non-linear) equality constraints of the optimization problem. Now, out of the design parameters, α_{i1}, α_{i2} and θ_i are kept within the limits $(-\pi, \pi)$. The parameters β_{1i}, μ_{1i} and β_{2i}, μ_{2i} describe the locations of the attachment points of the links to the human waist and thigh, respectively. The relations between these parameters are illustrated in Fig. 3 (representing the left side of the human body). The figure shows the top and front view of human torso around the hip joint[4] O.

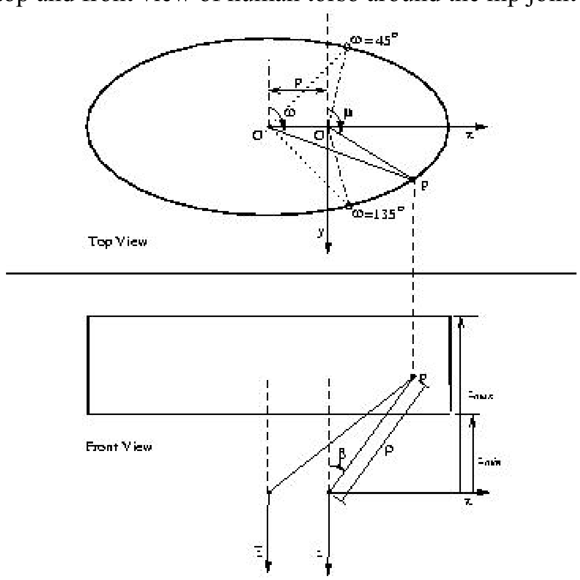


Figure 3: Description of the belt constraints at waist

For a point P on the belt (waist or thigh), β and μ are the corresponding parameters. Connecting the centre of the belt region O' to the point P, we get angle ω. As we can intuitively assign limits to ω, a mapping between μ and ω has been worked out to associate the limits of μ with that of ω and is derived by equating the definitions of point P as

[3] A linear system with condition number one is perfectly conditioned whereas a very large value of condition number corresponds to its ill-conditioning.
[4] The location of the human hip joint is taken as according to the human anatomy data.

$$\begin{bmatrix} \rho\sin\beta\sin\mu + p \\ -\rho\sin\beta\cos\mu \\ -\rho\cos\beta \end{bmatrix} = \begin{bmatrix} a\sin\omega \\ -b\cos\omega \\ -z \end{bmatrix}$$

providing the relations as

$$a\sin\omega = b\cos\omega\tan\mu + b \tag{8}$$

and

$$z = \frac{b\cos\omega}{\cos\mu\tan\beta}, \tag{9}$$

where a and b are major and minor axes of ellipse and p is the distance between O and O'. Eqn. 8 is solved numerically using Newton-Raphson method to get the value of ω for each required value of μ and this helps in calculating the limits for the former one to keep the later one in prescribed boundaries. Eqn. 9 provides the value of z for known values of β, μ and ω, and thus helps in computing limits $z_{\min}$ and $z_{\max}$. The limits assigned to ω and z are shown in the figure. Similar relations are used for corresponding parameters of the thigh but the limiting values are different. The constraints are used as non-linear inequality constraints for the optimization problem.

Next to these are constraints employed to prevent the self-crossing of links. This is achieved by putting limits on angles between u_i's and similarly between v_i's, for $i = 1,2,3$. Experiments with our program show that limiting the sum of link angles for each leg avoids the solutions at boundary. The optimization toolbox of MATLAB has been used for numerically solving the problem, as illustrated below.

B. Results of the optimization

The optimization of the design parameters is performed for a specific posture with values of ϕ_1, ϕ_2 and ϕ_3 (the angles representing the output configuration) as 0, $-\pi/4$ and 0, respectively. This configuration represents the posture with left thigh rotated by 45^o in downward direction which is the estimated mean position of the workspace of interest. The initial values of the design parameters are taken as

$$\alpha_{i1} = 0.5,\ \alpha_{i2} = 0.8,\ \beta_{1i} = 0.8,\ \beta_{2i} = 0.7 \quad \text{for } i = 1,2,3.$$
$$\mu_{11} = 0.8,\ \mu_{12} = 2,\ \mu_{13} = 3,\ \mu_{21} = 0.3,\ \mu_{22} = 1,\ \mu_{23} = 2.5.$$
$$\theta_1 = 0.8,\ \theta_2 = 1,\ \theta_3 = 1.5.$$

For calculations of non-linear constraints in Eqns. 8 and 9, values for a, b and p are taken as 20, 12 and $a/2$, respectively. Using *fmincon* in MATLAB the solution converged in 29 iterations to a function value of 1.06. The values for design parameters corresponding to this converged solution are given in Table 1.

i(*each leg*)	α_1	α_2	β_1	β_2	μ_1	μ_2	θ
1	−2.0796	2.0759	0.9814	0.9863	0.4545	−0.6834	−2.320
2	−2.7061	1.1840	1.0361	0.2416	0.4541	1.8604	−1.230
3	2.8274	−1.5894	0.5407	0.5032	2.8274	2.8274	−2.820

Table 1: Solution of the optimization problem

Fig. 4 shows the corresponding plot of all axes and presents the approximate picture of the selected representative pose. It is worth mentioning here that the shape of links is not part of the design of this paper and can be selected by the designer based on practical criteria.

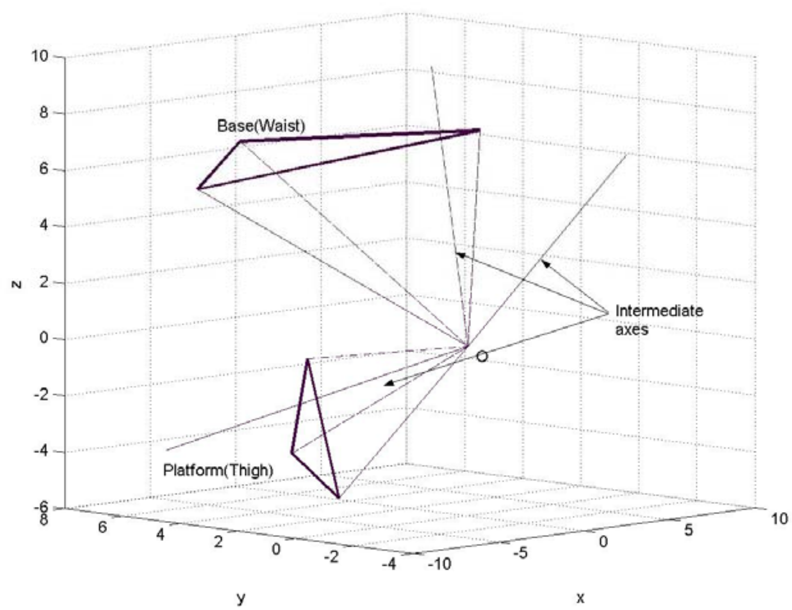


Figure 4: Plot of optimization result

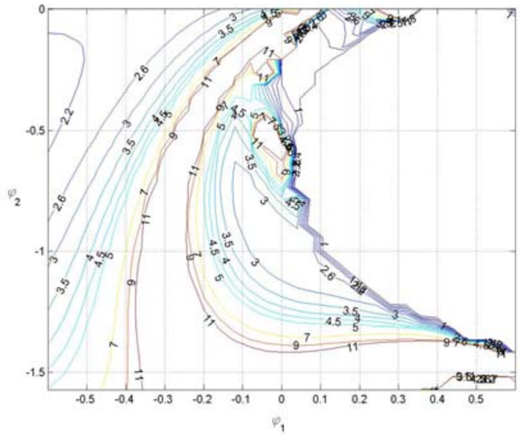
IV. Workspace Analysis

With the optimal design parameters in hand, we need to examine the workspace around the central pose to analyse the kinematic performance of the resulting structure for different postures. This requires the inverse kinematic equations of the mechanism which are easier to solve for a parallel manipulator. The detailed algorithm for solving the inverse kinematic problem of a spherical manipulator is presented in Gosselin et al [4]. The workspace analysis has been performed in the region, targetted for the manipulator synthesis, defined by the range of the output coordinates as

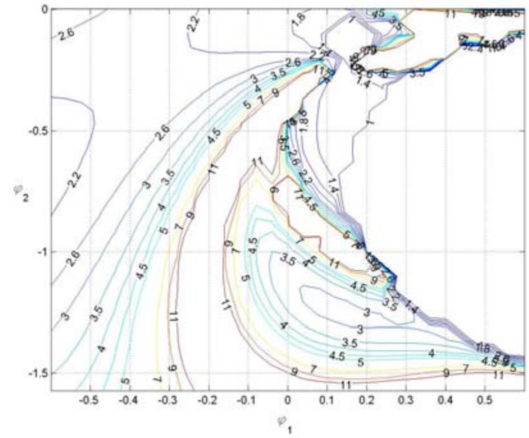
$$-0.6 \le \phi_1 \le 0.6\,,$$
$$-\pi/2 \le \phi_2 \le 0\,,$$
$$-0.5 \le \phi_3 \le 0.5\,.$$

Now, the actual workspace is rendered by using the approach of fixing one of the output coordinates, ϕ_3 in our case, and obtaining the contour plots of the dexterity from the other two. This makes it easy to identify the useful portion of the theoretical workspace. The contour plots of Jacobian condition number within domains of ϕ_1 and ϕ_2 with fixed values of ϕ_3 at 6 values $(-0.5, -0.3, -0.1, 0.1, 0.3, 0.5)$ are shown in Fig. 5.

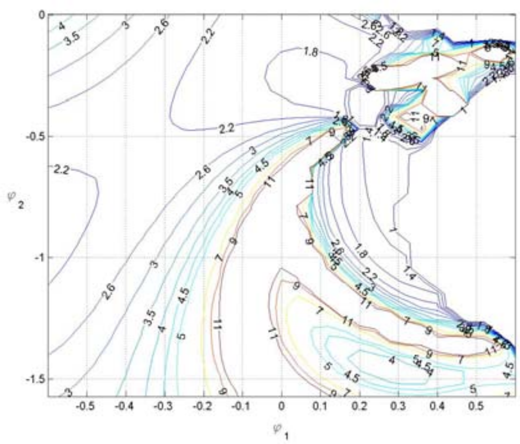
In the plots, contour curves corresponding to specific values of condition number have been shown for adjusting the number of curves and information delivery. The regions with very high condition number are emerging out as peaks and hence providing the information of poor transmission characteristics at those set of angles, but it has been observed that even though condition number at such regions are larger in comparison to around, but do not go much higher in magnitude and so can be taken as manageable configurations. Here, we take condition number more then 100 as bad and from the plots we observe that the worse values in our case are not more then 45. In the plots a few small regions appear near the boundary where the inverse kinematics gives complex results, representing the configurations which are not achievable.



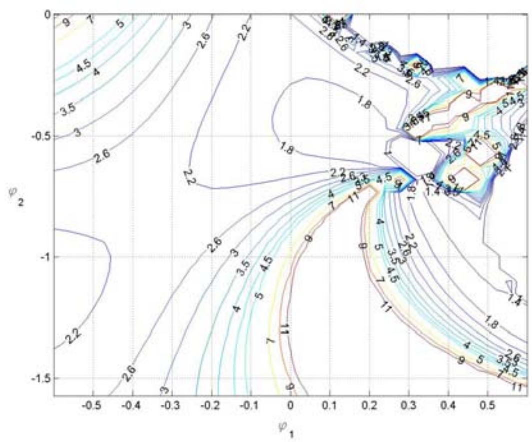
$(a)\quad \phi_3 = (-0.5)$



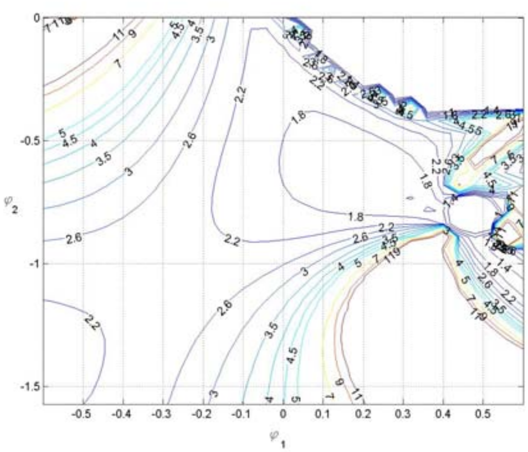
$(b)\quad \phi_3 = (-0.3)$



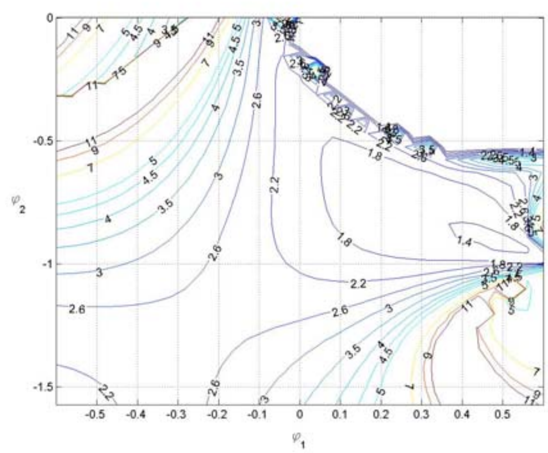
$(c)\quad \phi_3 = (-0.1)$



$(d)\quad \phi_3 = 0.1$



$(e)\quad \phi_3 = 0.3$



$(f)\quad \phi_3 = 0.5$

Figure 5: Dexterity plots showing sections of Cartesian workspace at different values of ϕ_3

V. Conclusion

In this paper, an optimal design of an exoskeleton hip-joint has been presented. Kinematic analysis required for the three-degrees-of-freedom spherical mechanism, used for developing the manipulator, has been derived. The design problem has been formulated as an optimization problem and the parameters necessary for developing the manipulator structure are optimized for a representative pose. The determination of workspace around the central configuration has been performed. The resulting plots depict the performance scenario of the optimized manipulator structure and highlight the ill-conditioned regions.
While the results yield an acceptable mechanism for the required purpose, dynamic performance was not considered. The design is for a disable patient and fast action is not required, so dynamic study of this manipulator is not worthwhile. The regions showing the unachievable configurations near the boundary indicate the scope of further study to explore possibilities to improve the design. Besides, detailed mechanical design is an important piece of work to be taken up as the next step.

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