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Design of a Four Legged Parallel Walking Robot to Go through a Narrow Hole

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Abstract: This paper designs a four legged parallel walking robot to go through a narrow hole. Topology design is conducted for a leg mechanism composed of four legs, base and ground, which constitute a redundant parallel mechanism. This mechanism is subdivided into four sub-mechanism composed of three legs. A motor vector is adopted to determine the 6x8 Jacobian of the redundant parallel mechanism and the 6x6 Jacobian of the sub-mechanisms, respectively. The condition number of the Jacobian matrix is used as an index to measure a dexterity. We analyze the condition numbers of the Jacobian over the positional and orientational walking space. The analysis shows that a sub-mechanism has lots of singularities within workspace but they are removed by a redundant parallel mechanism improving a dexterity. From the results, we can propose a parallel typed walking robot to enlarge walking space and stability region. The robot is designed by inserting an intermediate mechanism between upper and lower leg mechanisms. The robot is reasonably small so that it can go through a narrow hole.

Key Words: Legged parallel walking robot, Redundant Parallel Mechanism, Walking Robot, Dexterity, Condition Number.

1. INTRODUCTION

Researchers have proposed a variety of walking robots such as a multi-legged type like an insect (Garcia et al., 2006) and a biped type like a human being(Huang et al., 2001). The legged type robot requires lots of degrees of freedom with heavy weight. A Delta robot (Reg Dunlop, 2003) and a serial-parallel hybrid robot (Yusuke et al., 2001) are used for a walking robot to reduce the degrees of freedom and the weight. They consist of two leg-bases with three fixed legs each, and walk by moving each leg-base alternately. They can control the position and orientation of the bases to walk rough terrain as well as turn omni-directionally. However, the robots suffer from the lack of mobility and terrain adaptability since its walking space is limited due to unactuated legs. This research designs the Parallel Walking Robot (PWR) using the advantage of parallel mechanism such as dexterity and stability. Actuated legs are installed on the base, which produces the position and orientation arbitrarily. The robot can walk on the irregular surface of ground with small degree of freedom and has a large stability since the legs support the base in a wide space. Also parallel mechanism stacked in two layers with medium mechanism can generate a wide range of walking space to go through a narrow hole and climb up a wall. Therefore the proposed robot will be applied to painting and cleaning of in-and-out of a block for ship construction.

This research proposes three layered parallel walking robot and designs its leg mechanism with dexterity analysis. To enhance the dexterity, an extra leg is added to leg mechanism, which yields a redundant parallel mechanism composed of four legs, base and ground. To analyze the roles of the extra leg, we subdivide the four legged mechanism into four sub mechanisms and obtain their Jacobians. From the Jacobians' condition number, we present that all the singularities of sub mechanism are eliminated by adding the extra leg and the dexterity is improved by the redundant mechanism.

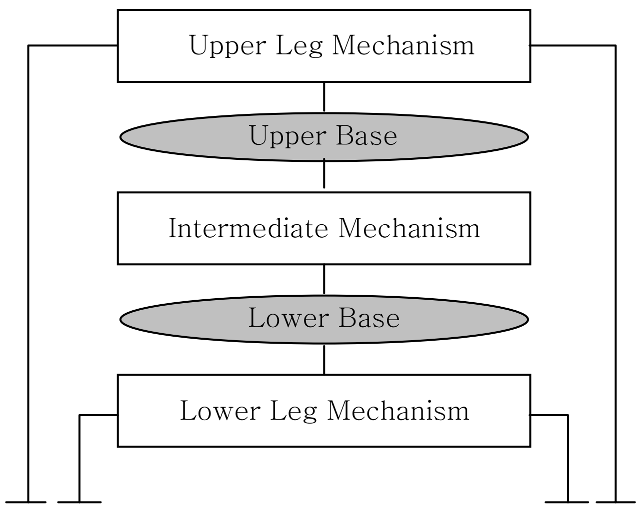


Fig. 1 Design concept of PWR

2. Three layered parallel walking robot

We design a robot which is able to walk stably in various environments, such as on rough terrain and up/down slopes. Also the robot should be small and light to go through a narrow hole and climb up a wall for painting or cleaning in the process of ship construction. For this purpose, we propose a parallel walking robot composed of three layered parallel mechanisms; an Upper Legged Mechanism (ULM) and a Lower Legged Mechanism (LLM) are attached to the upper base and the lower base, respectively, and Intermediate Mechanism (IM) is inserted into between the bases.

When the legs' feet step the ground to support a base, the base, support legs and ground form a parallel mechanism so that the legged mechanism generates the position and orientation of the base arbitrarily. When the legs' feet lift from the ground, they can swing for the next step. Therefore, the robot can walk rough terrain and up/down slopes with a large walking space and avoid the obstacle easily. Also, ULM, IM and LLM are independently operated, which are combined to generate a complex walking space which can't be made by a conventional walking robot.

3. Design of legged mechanism

When the legs' feet touch the ground, the legged mechanism composed of base, legs and the ground form a parallel mechanism which generates a walking space. From Gruebler's theory(Sandor et al., 1984), the degrees of freedom of the legged mechanism can be computed by

$$dof = \lambda\,(n-j-1)\sum_{m=1}^{j} d_m$$

where λ is equal to 6 for 3-D space, n is the total number of links, and j is the number of joints with d_m-DOF, The total degrees of freedom, *dof*, should be six to generate a positional and orientational walking space. All joints are assumed to have 1-DOF, i.e., $d_m = 1$. If there exist joints with 2 or more DOF, they can be replaced by two or more joints with zero-length linkages between them, and then Eq.(1) is rewritten as

$$6n = 5j + 12 \qquad (2)$$

If k-legs are installed to the base and their link trains have 6-DOF, Eq.(2) will be

$$n = 5k + 2 \qquad (3)$$

In the case of $k = 1$, this is a serial mechanism; in the case of $k \geq 2$, this becomes a parallel mechanism. In general, a parallel mechanism may have greater stiffness and can produce stronger forces than a serial one, but it contains the singularities at working space. Here, we design a redundant parallel mechanism with k=4 (see Fig.2) to remove the singularities.

Referring to Eq. (1), out of the legged mechanism's 24 joints, the 8 active joints can be chosen arbitrarily. Considering controllability and symmetry, we let four legged link trains be configured identically; each legged link train has two active joints and four passive joints. We choose the active joint which has a larger range of motion than the passive joint. Also an actuator should be easily installed at the active joint. As shown Fig.2(a), leg_i(i=1,2,3,4) are connected to the points B_i on the base through pin joints and the other pin joints are installed at the point N_i to swing the legs. We put a prismatic joint between points N_i and F_i to control the length of the leg and a spherical joint at the point F_i to orient the foot touching on the ground. As seen in Fig.2(b), leg_i becomes a 6-DOF link train from the base to the ground; the two pin joints generate 2-DOF (θ_{i1}, θ_{i2}), the prismatic joint produces 1-DOF (θ_{i3}), finally the spherical joint yields 3-DOF (θ_{i4}, θ_{i5} , θ_{i6}). Out of four joints, only the joints for θ_{i2} and θ_{i3} are active and the remaining joints for θ_{i1} , θ_{i4}, θ_{i5} and θ_{i6} are passive.

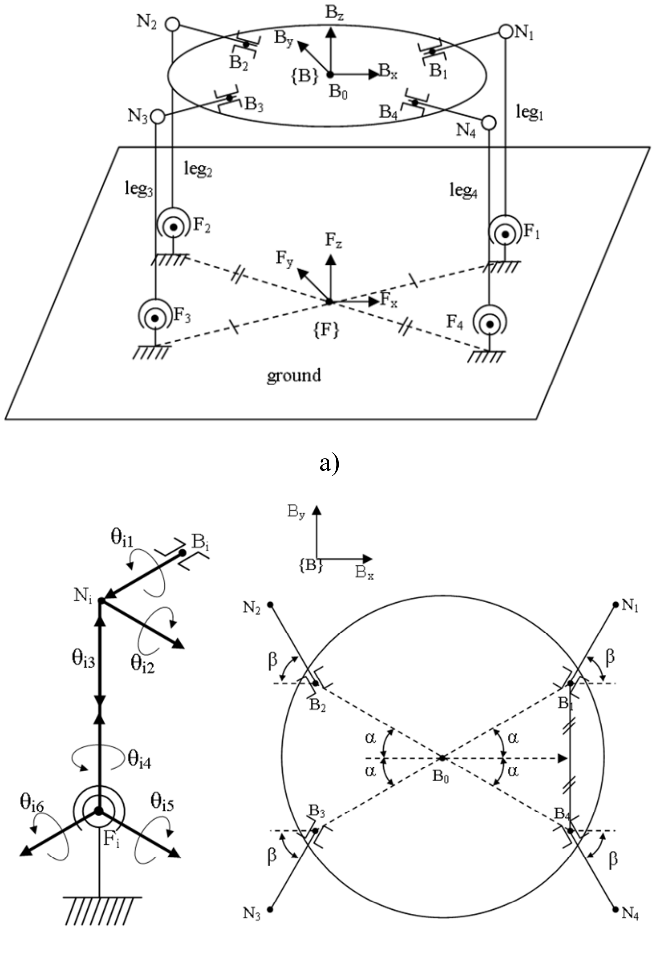


Fig. 2 Four Legged Parallel Mechanism. (a)Parallel mechanism composed of base, (i=1,2,3,4) and ground, (b) Link train of a , (c) Arrangement of on the base

The four legged robot can walk like a crab, which swings a leg while three legs step the ground. In the case of PWR, the base, legs and the ground form the parallel mechanism which generates the positional and orientational walking space, and the legs attached to base swing to produce another walking space.

4. Kinematics of legged mechanism

For kinematic analysis, we define reference points and coordinate frames as shown in Fig 2(c). Point B_0 is attached to the center of the base, the legs are located symmetrically about B_0 forming angles α and β with the horizontal lines. Frame {B} is assigned to the base with the origin at B_0; B_z is perpendicular to the plane defined by B_i(i=1,2,3,4), B_x is aligned with the line from B_0 to the center point between and B_1, B_4 and B_y is determined by a right hand rule. Points F_i(i=1,2,3,4) are located at 3D. To simplify the kinematics, we constrain the leg_2, which steps the point F_2 on the plane defined by F_i(i=1,3,4). The center of F_i(i=1,2,3,4) is defined as a point F_0 which is the origin of {F}; F_z is perpendicular to the plane defined by F_i(i=1,2,3,4), F_x is aligned with the line from F_0 to the center point between F_1 and F_4, and F_y is determined by a right hand rule.

When the position and the orientation of the base are given by the position vector and the rotation matrix of {B} with respect to {F}, i.e., ${}^F\overrightarrow{F_0B_0}$ and ${}^F R_B$, the inverse kinematics can calculate the active joint displacements, ${}^d\Theta$ = $[\theta_{12}, \theta_{13}, \cdots, \theta_{42}, \theta_{43}]^T$. On the contrary, when ${}^d\Theta$ is given, the forward kinematics can compute ${}^F\overrightarrow{F_0B_0}$ and ${}^F R_B$. Four legs are independently operated but leg_2 is treated as an extra leg constrained to the motion of the legged parallel mechanism. If the extra leg is constrained to the motion of the legged parallel mechanism, its kinematics is identical to that of a conventional parallel mechanism (Lee et al., 1999). This paper skips the kinematic analysis and describes singularity analysis. We can analyze the singularity from dexterity. Jacobian, which transforms the velocity and the force between the base and the actuators, is used for the measurement to express the dexterity (Klein et al., 1987).

A set of angular velocity of the base and linear velocity of a point B_0 is defined by a 6x1 array *twist*, i.e., Vel_{B_0} = $[\omega_{B_0}{}^T, V_{B_0}{}^T]^T$, where ω_{B_0} and V_{B_0} are angular velocity and linear velocity, respectively. The twist Vel_{B_0} can be expressed by a linear combination of motors of the link train:

$$Vel_{B_0} = \dot{\theta}_{i1}\,{}^{B_0}M_{i1} + \dot{\theta}_{i2}\,{}^{B_0}M_{i2} + \ldots + \dot{\theta}_{i6}\,{}^{B_0}M_{i6} \quad (4)$$

where a 6 x 1 array, ${}^{B_0}M_{ij}$, is the unit motor defined by a set of angular velocity of the base and linear velocity of point B_0 when the jth joint of the ith link train is actuated by a unit joint rate. If a set of motor vectors of each link train is defined as

$${}^{B_0}J_i = [{}^{B_0}M_{i1} \;\; {}^{B_0}M_{i2} \; \cdots \; {}^{B_0}M_{i6}] \text{(i=1,2,3,4)} \quad (5)$$

active and passive joint velocities, i.e., $\dot{\Theta}_i = [\dot{\theta}_{i1}, \dot{\theta}_{i2}, \ldots, \dot{\theta}_{i6}]^T$ is computed by

$$\dot{\Theta}_i = {}^{B_0}J_i^{-1}\, Vel_{B_0} \quad (6)$$

In order to derive the active joint velocities, we define ${}^{B_0}S_{ij} \in \Re_{1\times 6}$ (j=1,2,,6) as follows:

$$[{}^{B_0}S_{i1}{}^T \; {}^{B_0}S_{i2}{}^T \cdots \; {}^{B_0}S_{i6}{}^T] = {}^{B_0}J_i^{-1} \quad (7)$$

The active joint velocities are obtained by

$$\dot{\theta}_{ij} = {}^{B_0}S_{ij}\; Vel_{B_0} \quad (i\text{=1,2,3,4, } j\text{=2,3}) \quad (8)$$

Consequently, Vel_{B_0} is transformed to a set of active joint velocities, i.e., ${}^d\dot{\Theta}_i = [\dot{\theta}_{12}, \dot{\theta}_{13}, \ldots, \dot{\theta}_{42}, \dot{\theta}_{43}]^T$ by a Jacobian:

$${}^d\dot{\Theta}_i = J^{6\times 8}\; Vel_{B_0} \quad (9)$$

where $J_{6\times 8} \in \Re_{6\times 8}$ is the Jacobian composed of active joints. At least, three legs are necessary to support the base. Out of four legs, the combination of three legs, ${}_4C_3$, yields four sub-mechanisms. They cooperate to improve dexterity and remove singularity. To examine the role of an extra leg, we analyze the dexterity of the sub-mechanisms. From Eq.(9), four Jacobians of sub-mechanisms, J_i (i=1,2,3,4)$\in \Re_{6\times 6}$, are obtained by

$$\begin{aligned}
J_1 &= [{}^{B_0}S_{12}{}^T \;\; {}^{B_0}S_{13}{}^T \;\; {}^{B_0}S_{22}{}^T \;\; {}^{B_0}S_{23}{}^T \;\; {}^{B_0}S_{32}{}^T \;\; {}^{B_0}S_{33}{}^T] \\
J_2 &= [{}^{B_0}S_{12}{}^T \;\; {}^{B_0}S_{13}{}^T \;\; {}^{B_0}S_{22}{}^T \;\; {}^{B_0}S_{23}{}^T \;\; {}^{B_0}S_{42}{}^T \;\; {}^{B_0}S_{43}{}^T] \\
J_3 &= [{}^{B_0}S_{12}{}^T \;\; {}^{B_0}S_{13}{}^T \;\; {}^{B_0}S_{32}{}^T \;\; {}^{B_0}S_{33}{}^T \;\; {}^{B_0}S_{42}{}^T \;\; {}^{B_0}S_{43}{}^T] \\
J_4 &= [{}^{B_0}S_{22}{}^T \;\; {}^{B_0}S_{23}{}^T \;\; {}^{B_0}S_{32}{}^T \;\; {}^{B_0}S_{33}{}^T \;\; {}^{B_0}S_{42}{}^T \;\; {}^{B_0}S_{43}{}^T]
\end{aligned} \quad (10)$$

Any m x n matrix J can be factored into the following form, known as the singular value decomposition.

$$[A]_{m\times n} = [U]^T{}_{m\times m}\,[\textstyle\sum\;]^T{}_{m\times n}\,[V]^T{}_{n\times n} \quad (11)$$

where U and V are orthogonal matrices and $\sum$ is a diagonal formed with the singular values. In the case of sub-mechanism, A=J_i, m=6 and n=6, we have the six singular values $\sigma_1 \geq \sigma_2 \ldots \geq \sigma_6 \geq 0$. The condition number of Jacobian can be expressed by

$$k(J_i) = \sigma_1 / \sigma_6 \quad (12)$$

This ranges from 1 to infinite to be used for the measure of the dexterity. When $k(J_i)$=1, the mechanism is at the best configuration. As the condition number increases, the dexterity decreases to the singularity region.

5. Analysis of dexterity

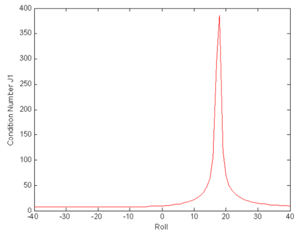
The dexterity of sub-mechanism is analyzed from the condition number. We design the small size of the legged mechanism:

1) The stroke of prismatic joint is 300mm,

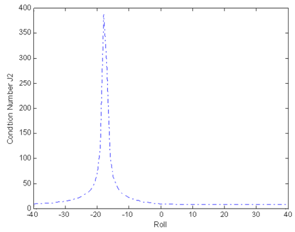
2) $\overline{B_0B_i}$=210mm, $\overline{B_iN_i}$=90mm, 300mm$\leq \overline{N_iF_i} \leq$ 600mm.

3) the range of pin joints is limited to ±45°, α =45° and β =20°.

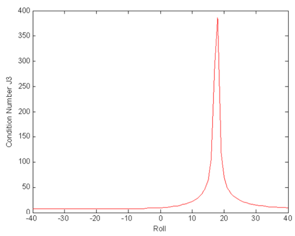
We analyze the dexterity over the entire walking space. Fig.6 shows the condition numbers of J_i (i=1,2,3,4) and $J_{6\times 8}$, respectively, on the X-Y walking plane, when yaw, pitch and roll are zero, and Z=400. The singularities arising in the three legged mechanism are removed by the four legged mechanism. Moreover, the dexterity is improved. Fig.7 represents the condition numbers of J_i (i=1,2,3,4) and $J_{6\times 8}$, respectively, when yaw and pitch are changed at roll =0, X=0, Y=0 and Z=400mm. Similar to the X-Y plane, the singularities are removed and the dexterities are improved.



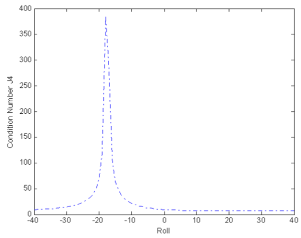
a) $k(J_1)$



b) $k(J_2)$



c) $k(J_3)$



d) $k(J_4)$

Fig. 3 condition number of sub-mechanism J_i (i=1,2,3,4)

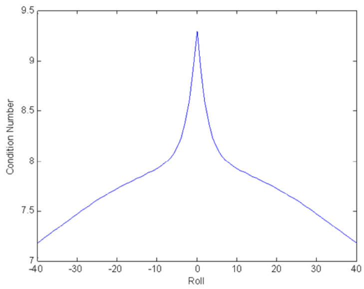


Fig. 4 Minimum condition number out of J_i (i=1,2,3,4)

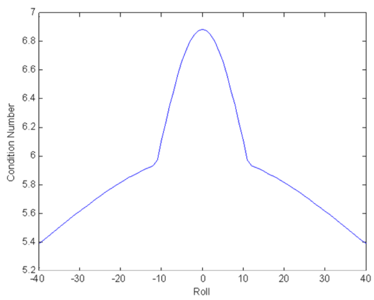
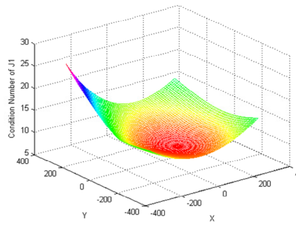


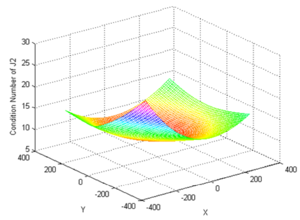
Fig. 5 Condition number of $J_{6\times 8}$

While legs' feet step the ground with $\overline{F_O F_i}$ =400 mm, the legged mechanism generates a roll motion of the base. Fig.3 shows the condition number of four sub-mechanisms.

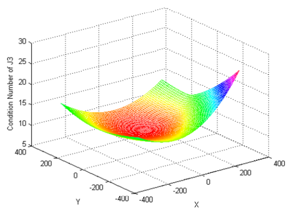
Four sub-mechanisms are symmetric so that $k(J_1)$=$k(J_3)$, $k(J_2)$=$k(J_4)$. The sub-mechanism-1, 3 have singularities in (+) direction but the sub-mechanism-2, 4 remove them. On the contrary, the sub-mechanism-2, 4 possess the singularities in (-) direction but the sub-mechanism-1,3 remove them again. Fig.4. is drawn by choosing the minimum condition number of sub-mechanisms. The condition number is below 10 so that all the singularities are eliminated. Fig.5 shows the condition number of the redundant legged mechanism, i.e., $k(J_{6\times 8})$. Comparing with the sub-mechanism, the dexterity of redundant mechanism is extremely improved; the maximum condition number decrease from 10 to 8 and the condition numbers mostly range below 6.



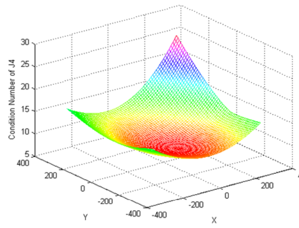
a) $k(J_1)$



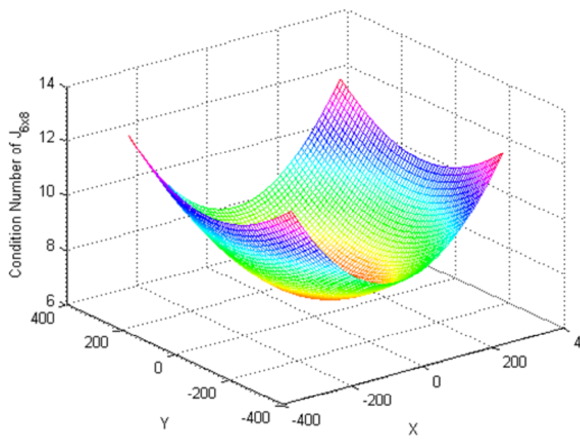
b) $k(J_2)$



c) $k(J_3)$

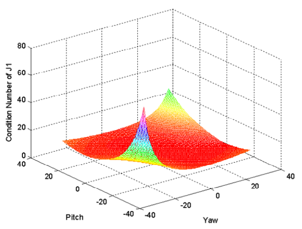


d) $k(J_4)$

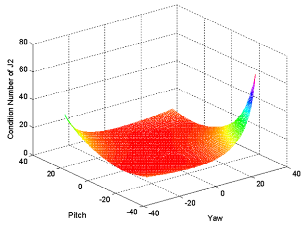


e) $k(J_{6\times 8})$

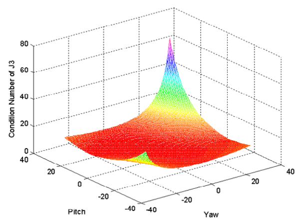
Fig. 6 Condition number of J_i (i=1,2,3,4) and $J_{6\times 8}$ on the X-Y walking plane when yaw, pitch and roll are zero at z=400mm



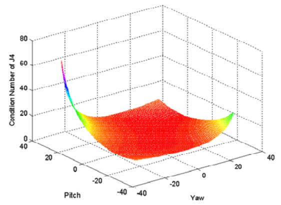
a) $k(J_1)$



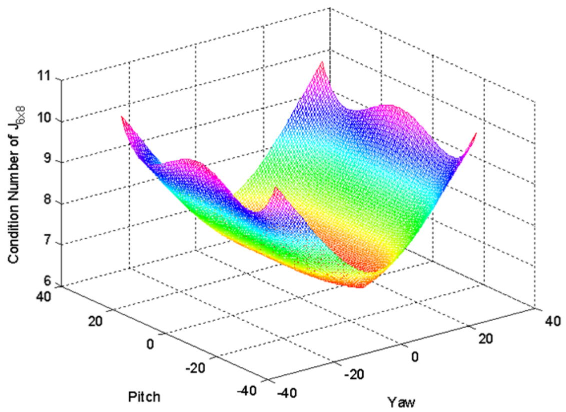
b) $k(J_2)$



c) $k(J_3)$



d) $k(J_4)$



e) $k(J_{6\times 8})$

Fig. 7 Condition number of J_i (i=1,2,3,4) and $J_{6\times 8}$ on the Yaw-Pitch Orientation when roll is zero at X=0, Y=0, Z=400mm

6. CONCLUSIONS

We design a four legged walking robot to improve the dexterity. Topology design is conducted for a leg mechanism composed of four legs, base and ground, which constitute a redundant parallel mechanism. From the topology design, we determine its degrees of freedom and select active and passive joints. The four legs were arranged symmetrically to support the base. Two active joints and four passive joints were installed in each leg. The legged mechanism is subdivided into four sub-mechanisms composed of three legs.

A motor vector is adopted to determine the Jacobian of the redundant parallel mechanism and the Jacobian of the sub-mechanisms, respectively. The condition numbers of the Jacobian matrices are used as an index to measure a dexterity. Symmetric sub mechanisms eliminate all the singularities within walking space by cooperation of four sub mechanism. Also, dexterity has been improved up to 20% by adding an extra leg for the redundant mechanism. Based on the analysis of the legged mechanism, a variety of parallel walking robots will be developed by stacking the legged mechanism into two layers. We aim to develop a walking robot which can go through a narrow hole for ship construction.

ACKNOWLEDGMENTS

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