This paper deals with a new planar parallel manipulator, kinetic energy of this mechanism, designing controller. The translation movements are decoupled from rotation. The control algorithm of parallel robot satisfying partial decoupling between translation and orientation degrees of freedom is synthesized. Simulation result of control algorithm in desired trajectory of end-effector of robot is shown. Here parallel manipulator control algorithm while intersecting singular zones is considered.

**KEYWORDS**

Degree of freedom, Singularity, Decoupled manipulator, Kinetic energy, Control algorithm.

1. INTRODUCTION

The idea to design a new partially decoupled parallel manipulator is following. We use well known planar five-bar mechanism and add the third kinematic chain containing two prismatic kinematic chains formed as planar parallelograms (Fig. 1, 2)\[1\]. Let us consider the degree of freedom of this planar parallel manipulator which is to be developed. Here we can see three kinematic chains[2]. Two of them are used for translation of the output link and one of them is used for rotation of this link[3].

\[
\begin{align*}
\theta_1 &= 2\tan^{-1}\frac{e_1 + e_2 - e_3 - e_4}{e_1 - e_2} \\
e_1 &= 2Y_A X_B - 2Y_B X_A \\
e_2 &= 2X_A Y_B - 2X_B Y_A \\
e_3 &= X_A^2 + Y_A^2 - 2X_B Y_A + Y_B^2 - 2Y_A Y_B + e_2 - e_1^2
\end{align*}
\]

(4)

For the second kinematic chain is similar relation.

Then kinematic modeling in term of speed of robot is considered. It is possible to express the solution of a problem on positions in the form of implicit functions. Then these functions are differentiated, we have\[10\]:

\[
\begin{align*}
\frac{\partial F_x}{\partial x} + \frac{\partial F_y}{\partial y} = 0 \\
\frac{\partial F_y}{\partial x} + \frac{\partial F_y}{\partial y} = 0
\end{align*}
\]

(6)

On the left side we have the matrix A, on the right = a matrix B. These equations are used for the analysis singularities. The first type of singularity corresponds to the determinant of matrix B goes to zero. The second type of singularity corresponds to the degradation of matrix A[9].

\[
\begin{align*}
2X_A - 2X_B - 2\sin\theta + 2Y_A - 2Y_B - 2\cos\theta \\
0X_A - 2X_B - 2\sin\theta + 2Y_A - Y_B - 2\cos\theta
\end{align*}
\]

(7)

The third type of singularity corresponds to the degradation of both matrices. In order to explain the third kinematic chain, matrices A and B must be converted[12].
ing into account the possible relationship issues have

grees of freedom corresponding to an output link, the robot, and also introduce
ting.

\[ \begin{align*}
    A &= \begin{bmatrix}
            \frac{\partial F}{\partial x} & \frac{\partial F}{\partial y} \\
            \frac{\partial G}{\partial x} & \frac{\partial G}{\partial y}
        \end{bmatrix} \begin{bmatrix}
            x \\
            y
        \end{bmatrix}, \\
    B &= \begin{bmatrix}
            \frac{\partial F}{\partial \theta} & \frac{\partial F}{\partial \phi} \\
            \frac{\partial G}{\partial \theta} & \frac{\partial G}{\partial \phi}
        \end{bmatrix} \begin{bmatrix}
            \theta \\
            \phi
        \end{bmatrix}, \\
    C &= \begin{bmatrix}
            \frac{\partial F}{\partial \alpha} & \frac{\partial F}{\partial \beta} \\
            \frac{\partial G}{\partial \alpha} & \frac{\partial G}{\partial \beta}
        \end{bmatrix} \begin{bmatrix}
            \alpha \\
            \beta
        \end{bmatrix}
\end{align*} \tag{8} \\

The third chain provides rotation with a single gear ratio. For the analysis of previous unknown type of singularity of the fourth modification of the proposed matrix. Taking into account the possible relationship imposed by the third kinematic chain [13].

\[ \begin{bmatrix}
        (X_p - X) \sin \theta + (Y_p - Y) \cos \theta \\
        0
    \end{bmatrix} = \begin{bmatrix}
        B \\
        0
    \end{bmatrix} \begin{bmatrix}
        \theta \\
        \phi
    \end{bmatrix}, \quad \begin{bmatrix}
        (X_p - X) \sin \phi + (Y_p - Y) \cos \phi \\
        0
    \end{bmatrix} = \begin{bmatrix}
        \theta \\
        \phi
    \end{bmatrix}, \quad \begin{bmatrix}
        (X_p - X) \sin \alpha + (Y_p - Y) \cos \alpha \\
        0
    \end{bmatrix} = \begin{bmatrix}
        \alpha \\
        \beta
    \end{bmatrix} \tag{9} \\

According to it the fourth type of singularity has been found.

2. KINETIC ENERGY OF 3-DOF PLANAR PARALLEL MANIPULATOR

Energy relations that takes place in the parallel robot structure are considered. This question is important for modeling dynamics of the robot and control.

The general energy is equal to the sum corresponding to a output link, and intermediate links [14].

\[ T = T_1 + T_2 + T_3 \tag{10} \]

To determine the energy we use schema (Fig. 6). In particular, for the intermediates links

\[ T_{ii} = \frac{1}{2} m_a v_{ai}^2 + \frac{1}{2} J_{ai} \omega_i^2 \quad J_{ai} = \frac{1}{12} m_a l_i^2 \tag{11} \]

In these equations include inertial parameters of links and their speed. For studying dynamics of the robot it is necessary to have partial derivatives of these expressions on the generalized velocities and coordinates. These relations are quite complicated in nature. In particular, we find differentials from the following expressions [16]:

\[ \begin{align*}
    &B = a_1 \gamma_i^2 + a_2 \gamma_i^2, \quad \gamma_i = 2a_i \gamma_i + 2d_i \gamma_i + (r_i)^2 + r_i^2 \gamma_i^2 - 2a_i d_i \gamma_i + a_i^2 \gamma_i^2 + a_i d_i \gamma_i + d_i^2 \gamma_i^2, \\
    &C = a_1 \gamma_i^2 + a_2 \gamma_i^2, \quad \gamma_i = 2a_i \gamma_i + 2d_i \gamma_i + (r_i)^2 + r_i^2 \gamma_i^2 - 2a_i d_i \gamma_i + a_i^2 \gamma_i^2 + a_i d_i \gamma_i + d_i^2 \gamma_i^2 \tag{12}
\end{align*} \]

Where the coefficients $k_1, \ldots, k_4$ depend on manipulator parameters.

3. ANALYSIS MANIPULATOR DYNAMICS

This part deals with the dynamic analysis of the parallel robot structure. We use the type II Lagrange equations. First, we solve the inverse dynamic problem. The law of movement is known and it is necessary to find the control action in actuator. Corresponding algorithms and programs have been developed, the concrete example of the parallel robot (a Fig. 7) is considered. The simulation results are shown in Fig. 9, 10, 11.

\[ \begin{align*}
    &v(t) = \frac{\partial \phi}{\partial t}, \quad \phi(t) = \frac{\partial \theta}{\partial t}, \\
    &\phi(t) = \frac{\partial \theta}{\partial t}
\end{align*} \tag{14} \]

Thus generalized coordinates should change as follows.

\[ \begin{align*}
    &q(t) = q_p + \frac{\partial \phi}{\partial t}, \quad \phi(t) = \frac{\partial \theta}{\partial t}, \\
    &\phi(t) = \frac{\partial \theta}{\partial t}
\end{align*} \tag{13} \]

Planning trajectory of the robot is important for control. In particular, we can choose from a variety of trapezoidal velocity curves (Fig. 12).

\[ \begin{align*}
    &q(t) = q_p + \frac{\partial \phi}{\partial t}, \quad \phi(t) = \frac{\partial \theta}{\partial t}, \\
    &\phi(t) = \frac{\partial \theta}{\partial t}
\end{align*} \tag{14} \]

4. CONTROL ALGORITHMS

This section deals with control algorithm of parallel robot structure. The algorithm proposed by R.Paul and tested on robot with consistent structure. Idea behind the algorithm is that compensating mutual influence between degrees of freedom of the robot, and also introduce control algorithm of the factors that take into account weight led to drive mass and the moment of inertia of the manipulator.

It is necessary to notice that in paper the interferences caused by a configuration of the robot and the generalized speeds are compensated only. Compensation of the mutual influence caused by accelerations are not carried out because the accelerometers make big noise. In addition, influence of accelerations is supposed not so high because of small speeds. The structure of control system is shown in Fig. 13.

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We have parameters of the DC separate-excited Actuator as following:

Table 1: Actuator Parameters

| Parameters | Value | Unit | Parameters | Value | Unit |
|------------|-------|------|------------|-------|------|
| u          | 25    | V    | K          | 5.7E-2| Nm/A |
| a          | 3.9   | A    | Kv         | (u Ra'*)/w | V/sec/rad |
| Ra         | 1.1   | \Omega | Mc       | 0.191 | Nm |
| La         | 0.9E-3| H    | P          | 60    | Wat  |
| Jf         | 0.57E-4| Kg m² | n | 3000 | Round/minute |
| B          | 1.7E-2| Nm   |            |       |      |

As can be seen from the graphs, the maximum error in the generalized coordinates of the first case are 5.48 % and 0.49 %; in the second case are 2.2 % and 0.17 %.

5. PARALLEL MANIPULATOR CONTROL WHILE INTERSECTING SINGULARITY ZONES

It is known that there could be a parallel manipulators control loss in singular configuration that is why we suggest the use of additional actuator that is shown in Fig. 17.

Figure 17: Configuration of the third chain for solving singularity

Singular configurations are very regular phenomenon in parallel manipulators. Each such configuration presents an intersection point of the trajectory and the singular zone. There should be a procedure how to pass through such a position. We advice the use of additional actuator. This actuator should be introduced into short-term operation.

The point is that approaching singular configurations the system of equations becomes degenerate, and required generalized forces (in actuators) become too large. In this case an additional actuator should be used, which has to be taken into consideration in the control algorithm.

In parallel manipulator (Fig.2) the singular configuration is manifested by links AB and AC forming one line. This singular zone is one-dimensional, as in case of constant relative position of the above-mentioned links the manipulator has only one degree of freedom.

We introduce the criterion of singular configurations: the overrun of the generalized moment’s marginal tolerance value. It is necessary that the moment surpass the nominal value not more than two times. On reaching such configuration there should be a load transfer with taking extra actuator into account.

The singular configuration wouldn’t be a singular one if the actuators are situated in B, C and H and B pairs (Fig.2). The algorithm could be realized this way: at initial stage the three main actuators B, C and H are in operation. When the moment of one of them reaches the surpass nominal value, the other extra actuator (Fig. 17) is put into operation.

6. CONCLUSION

A new planar parallel manipulator is considered. The translation movements are decoupled from rotation. Kinematic modeling of parallel robot is realized and the algorithms and criteria of its singularities are developed corresponding to loss of degree of freedom or loss of controllability, a new kind of singularity is found;

Dynamic modeling of parallel robot is realized based on energy conditions, the direct and inverse dynamic problems of parallel robot.

The control algorithm of parallel robot satisfying partial decoupling between translation degrees of freedom is synthesized.

Suggestion solving for parallel manipulator control while intersecting singularity zones.

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