Link Length Control using Dynamics for Parallel Mechanism with Adjustable Link Parameters -Verification with Experiment using Actual Mechanism-

Wataru TANAKA, Tatsuo ARAI, Kenji INOUE and Tomohito TAKUBO

Abstract—There has been always a workspace problem with parallel mechanisms. We have proposed a parallel mechanism with linear passive joints to adjust link length. This parallel mechanism can have different workspaces by adjusting link length. When these workspaces are combined, it has larger workspace. We have tried to control the link lengths of this parallel mechanism not actively but passively using dynamics. We have presented the possibility of the proposed control algorithm of these passive linear joints to adjust the link lengths using dynamics with the simulation. This paper has investigated with the experiments in the case of a simple planer prototype.

Index Terms—Parallel Mechanism, Dynamics, Adjustable Mechanical Parameters, Passive Joint Control

I. INTRODUCTION

 \mathbf{P} arallel mechanisms have good advantages, compared with conventional articulated arms in the aspects of high speed capability, large force actuation, high positioning accuracy, modularity, and simple inverse kinematics solution. The large force actuation is very useful to the construction activity, for example the handling or positioning of the huge and heavy materials. Parallel mechanism will be applied to the machine which is used the construction activity. There are the papers pf the parallel mechanism for the heavy material handling [1][2]. The only drawback of parallel mechanism is its small workspace, since the in-parallel configuration naturally brings link interference and this limits the motion range of links and end-effecter. The construction activity requires the large workspace. There have been some researches aiming to enlarge the workspace of specific parallel mechanisms by analyzing their kinematics and optimizing link parameters [3], although they have not provided a sufficient answer. A large workspace is preferable in general. It could be achieved by compensating additional motion, such as, supplementing another degree of freedom in its base or end [4]. A redundant configuration with mixture of parallel and serial mechanisms has been proposed in this aspect [5]. However, if the application is carefully specified, even a small workspace of the parallel mechanism could work effectively, such as, in the application of micro manipulation [6].

All of the large workspace may not be always required in one task, and the workspace may be divided into smaller sub-workspaces corresponding to individual tasks (**Fig.1**). This is our basic idea in the paper [7]. If each sub-workspace can be covered by each corresponding parallel mechanism that is not different individuality but a single mechanism with differently adjusted mechanical parameters, the whole workspace is to be achieved by just one machine.

Some tasks may be divided into their sub-tasks, which do not always have to be done at the same time. If each task corresponds to each individual sub-workspace, the whole workspace is not covered by a single fixed machine. Our idea is to cover each sub-workspace by a machine that has adjustable properties in its mechanical parameters. There are some mechanical parameters which can be changed, such as base plate parameters, end-effecter parameters and link parameters. Because link parameters can be adjusted more largely than other parameters, the workspace is also larger. In this paper, therefore, the parallel mechanism with adjustable link parameters is investigated (**Fig.2**).



Fig.1. The combinational workspace

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Fig.2. The parallel mechanism with adjustable link parameters

The link length of this parallel mechanism could be adjusted, passively or actively. A mechanism with actively adjusted link length is a kind of redundantly actuated mechanism and it would be uninteresting due to its high cost of many actuators. Hence, the proposed idea is to adjust link length without actuators. There are two methods of adjusting link length; manually and automatically. If link length is adjusted manually, there is a need to stop the mechanism for adjustment. Hence, we have attempted to adjust the link length automatically. Therefore, we need to control passive joints to adjust the link length automatically. The control of serial manipulator with passive joint using the dynamics has been studied [10][11]. We apply this to parallel mechanism with adjustable link parameters and control the passive linear joints to adjust the link length using its dynamics.

Link mechanisms including parallel mechanism have complicated and interfered dynamics naturally. The joint torque is generated by the velocities and accelerations of other joints as well as of the joint itself. Each link has inertia, Coriolis and centrifugal forces and they bring torque and force in every joint. In other words they can contribute to drive any joint, which has no actuator. As shown in the research of serial arm cases, this is a non-holonomic property. This is our basic idea that if we properly control the motion of active joints in our parallel mechanism then the adjustable link with no actuator can be controlled arbitrarily.

In this paper, we apply this idea to the developed parallel mechanism with adjustable passive linear joints. First, we will discuss the proposed algorithm and investigate with experiments using the prototype 2-DOF planer parallel mechanism.



Active rotary joint

Fig.3. The parameters of the parallel mechanism with adjustable link parameters

In this paper, we discuss the algorithm of the link length control using the planer 2-DOF rotary actuated parallel mechanism with adjustable link length as shown in **Fig.3**. This mechanism has the passive linear joint on each link, which is closer to the end-effecter, with the lock system. When the lock is put ON or OFF, the passive linear joint can be fixed or released respectively.

The joint r_{11} and r_{21} are the active rotary joints and θ_{11} , $\dot{\theta}_{11}, \ddot{\theta}_{11}, \theta_{21}, \dot{\theta}_{21}$ and $\ddot{\theta}_{21}$ show the displacement, velocity and acceleration vector of each active rotary joints respectively. The joint r_{12} and r_{22} are the passive rotary joints and θ_{12} , $\dot{\theta}_{12}, \ddot{\theta}_{12}, \theta_{22}, \dot{\theta}_{22}$ and $\ddot{\theta}_{22}$ show the displacement, velocity and acceleration vector of each passive rotary joint respectively. The joint l_{12} and l_{22} are the passive linear joints and L_{12} , $\dot{L}_{12}, \ddot{L}_{12}, L_{22}, \dot{L}_{22}$ and \ddot{L}_{22} show the displacement, velocity and acceleration vector of each passive linear joint. L_{12} is the length between joint r_{12} and the end-effecter, L_{22} is the length between joint r_{22} and the end-effecter. o_0 shows the origin of the base frame and the position of the joint r11. L_0 shows the position of the joint r_{12} . L_{11} shows the length between the joint r_{11} and r_{12} . L_{22} shows the length between the joint r_{21} and r_{22} . x, \dot{x} and \ddot{x} show the displacement, velocity and acceleration vector of the end-effecter. Θ , $\dot{\Theta}$ and $\ddot{\Theta}$ show the displacement, velocity and acceleration of the all of the joints.

The equations of motion of the planer 2-DOF rotary actuated parallel mechanism with passive linear joints is formulated as follows:

$$\begin{bmatrix} \tau_{\theta_{11}} \\ \tau_{\theta_{21}} \\ f_{L_{12}} \\ f_{L_{22}} \end{bmatrix} = M(\Theta) \begin{bmatrix} \ddot{\theta}_{11} \\ \ddot{\theta}_{21} \\ \ddot{L}_{12} \\ \ddot{L}_{22} \end{bmatrix} + B(\Theta, \dot{\Theta})$$
(1)

 $M(\Theta)$ shows the acceleration related matrix, $B(\Theta, \Theta)$ shows the matrix which has the Coriolis and centrifugal force vector, the gravity loading force vector and friction force vector. In this paper, however, the gravity loading force vector is ignored, because we discuss the planer manipulator. $\tau_{\theta_{11}}$ and $\tau_{\theta_{21}}$ show the torque vector of the active rotary joints r_{11} and r_{21} respectively. $f_{L_{12}}$ and $f_{L_{22}}$ show the force vector of the passive linear joints l_{12} and l_{22} respectively.

When the lock of each passive joint is put off, their forces become zero. In other words, $f_{L_{12}}$ and $f_{L_{22}}$ become zero as follows:

$$\begin{bmatrix} \tau_{\theta_{11}} \\ \tau_{\theta_{21}} \\ 0 \\ 0 \end{bmatrix} = M(\Theta) \begin{bmatrix} \ddot{\theta}_{11} \\ \ddot{\theta}_{21} \\ \ddot{L}_{12} \\ \ddot{L}_{22} \end{bmatrix} + B(\Theta, \dot{\Theta})$$
(2)

We set the desired accelerations of the passive linear joints l_{12} and l_{22} are $\ddot{L}_{12,d}$ and $\ddot{L}_{22,d}$ respectively. From the equation (2), we can formulate the control equation as follows:

$$\begin{bmatrix} \boldsymbol{\tau}_{\theta_{11}} \\ \boldsymbol{\tau}_{\theta_{21}} \end{bmatrix} = f_{cotrol \ equation}(\ddot{L}_{12,d}, \ddot{L}_{22,d})$$
(3)

The equation (3) can estimate the torques of the active rotary joints r_{11} and r_{21} for realizing the desired accelerations of the passive linear joints l_{12} and l_{22} . The detail of this control equation is shown in our previous paper [13],

From above mentioned, we can control the passive linear joints l_{12} and l_{22} using this control equation (3) as follows. First, we estimate the desired accelerations of the passive linear joints from desired displacements of the passive linear joints l_{12} and l_{22} . Next, these desired accelerations are input in the control equation (3), and we can obtain the torques of the active rotary joints r_{11} and r_{21} for realizing the desired accelerations of the passive linear joints of the passive linear joints l_{12} and l_{22} .

III. EXPERIMENTS

A. Planer 2-DOF rotary actuated parallel mechanism with passive linear joint on each link





Fig.4. The planer 2-DOF rotary actuated parallel mechanism with the passive linear joint on each link

In this paper, we try to investigate the proposed algorithm of link length control using the actual prototype of the planer 2-DOF rotary actuated parallel mechanism with passive linear joint on each link, shown in Fig.4. This parallel mechanism has the passive linear joint on each link which is closer the end-effecter. This passive linear joint is consisted of the two rigid bodies: one is the fixed part, the other is the rod which is the movable through the center of the fixed part. Moreover, These passive linear joints have the lock system using the air pressure (Fig.5). When the lock system is given the air by an air compressor, the lock system can fix the linear passive joint. There is a solenoid-operated valve between the air compressor and the lock system. We can control the air delivery using PC. The passive linear joint has the linear encoder sensor. We can obtain the displacement of the passive linear joints by measuring its sensor value.

There are the active rotary joints using DC servomotor on the base plate. The active rotary joint has the rotary encoder. We can obtain the displacement of the active rotary joint by measuring its sensor value.

Fig.6 shows the whole control system.



Linear encoder sensor Air pressure lock system

Fig.5. The passive linear joint with the air pressure lock system and the linear encoder sensor



Fig.6. The system

Each parameter value of this mechanism is as follows: $L_0 = 15.0$ [cm] and $L_{11} = L_{21} = 20.0$ [cm] and the initial link length $L_{12,initial}$ and $L_{22,initial}$ is 22.0[cm] respectively. The mass of one of the links, which is more distant from end-effecter, is 0.50[kg]. The mass of the fixed part of links, which is closer to end-effecter, is 0.50[kg], the mass of the rod is 0.20[kg].

The mass center of each link is the center of its link, and we assume that all of link frame axis and its principal axis of inertia are in the same direction. The gravity is ignored because this mechanism is fixed parallel to the ground.

Setup the trajectory of the transformation of the passive

linear joints

First, we set up the trajectories of the desired link length $\ddot{L}_{12,d}$ and $\ddot{L}_{22,d}$. The desired displacements, velocities and accelerations of the passive linear joints are estimated from these trajectories. We estimate the torques of the active rotary joints to obtain the desired accelerations. We input the torques to the actual mechanism. We observe the displacement of the passive linear joints using the linear encoder sensors.

In this experiment, we setup the both of the desired link length $\ddot{L}_{12,d}$ and $\ddot{L}_{22,d}$ are 24.5[cm] shown in **Fig.7**. In other words, we try to transform the link length of L_{12} and L_{22} from 22.0[cm] to 24.5[cm]. The time T_1 is 0 [s], when the locks of the passive linear joints are put OFF, in other words, the passive linear joints are put ON, the passive linear joints are fixed, set T_2 =0.12[s]. We set the sampling time is 10[ms].



Fig.7. The desired link length

Next, we setup the desired trajectory of the transformation of the passive linear joints as follows. When the lock of the passive linear joints is put ON or OFF, it is need that the velocity of the passive linear joints is zero [cm/s]. Moreover, it's not desirable to transform the passive linear joints drastically. Consequently, we setup the desired displacement, velocity and acceleration of the passive linear joints as shown in **Fig.8**, **Fig.9** and **Fig.10**. The trajectory of the velocity transformation of the passive linear joints shapes the trapezoid. In Fig.8, Fig.9 and Fig.10, the vertical axis presents the displacement [cm], velocity [m/s] and acceleration [cm/s^2] respectively, and the horizontal axis presents the time[s].



Fig.8. The desired lengths of the passive linear joints L_{12} and L_{22}



Fig.9. The desired velocities of the passive linear joints \dot{L}_{12} and \dot{L}_{22}



Fig.10. The desired acceleration of the passive linear joints $\,L_{12}\,$ and $\,\ddot{L}_{22}\,$



Fig.11. The estimated torques of the active rotary joints $\tau_{\theta_{11}}$ and $\tau_{\theta_{21}}$ for realizing the desired accelerations of the passive linear joints

Moreover, we setup the pre-velocity of the end-effecter. The pre-velocity is the velocity of the end-effecter before the locks of the passive linear joints are released. This velocity is 80[cm/s] and the direction is y-axis. The position of the end-effecter, when the locks of the passive linear joints are released, is (x,y)=(7.5,15.0)[cm]. The pre-velocity of the end-effecter not always have to be setup. However, through the experiments we can obtain the information which we can control the passive linear joints more easily, when the mechanism has inertia force when the locks of the passive linear joints are released. Consequently, we have setup the pre-velocity of the end-effecter.

Using the control equation (3) and the trajectories of the transformation of the passive linear joints (Fig.8, Fig.9 and Fig.10), we estimate the torques of the active rotary joints to realize the desired transformation of the passive linear joints as shown in **Fig.11**. From the estimated torques of the active rotary joints, the accelerations, velocities and displacements of the active rotary joints are estimated using forward dynamics. These accelerations velocities and displacements are input in the planer 2-DOF rotary actuated parallel mechanism with passive linear joint on each link.

B. Results

We observe the actual mechanism in controlling using the proposed algorithm.

Fig.12 shows the trajectory of the realized transformation and desired transformation of the displacements of the passive linear joints l_{12} . **Fig.13** shows the trajectory of the realized transformation and desired transformation of the displacements of the passive linear joints l_{22} . These trajectories of the realized transformation are estimated from the linear encoder sensor set the passive linear joints. In these graphs, the horizontal axis presets the time [s], the vertical axis presents the displacements of the each passive linear joints.

Fig.12 and Fig.13 show that the displacements of the passive linear joints can be transformed using the proposed algorithm

of the link length control. From this fact, using the torques of the active rotary joints set the base plate, the passive linear joints set the each joint can be transformed.

However, these realized transformations don't match the desired transformation of the passive linear joints as shown in Fig.12 and Fig.13. This is because the influence the modeling error of the mechanism, for example, the friction force of each joints, the link mass and so on, and the time-lag of the response of the lock systems based on the air pressure and so on.

The friction force has big influence in such mechanism control. However, it is very difficult that the friction force is measured precisely. Moreover, the precise dynamical parameters cannot be estimated easily. In this paper, we only perform the feed forward control. Consequently, we need perform the feed back control using the value which can be obtained with the linear encoder sensor set the passive linear joints.



Fig. 12. Desired and realize length of L_{12}



Fig.13. Desired and realize length of L_{22}

IV. CONCLUSION

In this paper, we have discussed the link length control for parallel mechanism with adjustable link parameters. We have investigated the proposed algorithm using the actual mechanism which is called the planer 2-DOF rotary actuated parallel mechanism with the passive linear joints on each link.

From the results, we have represented the possibility of the control using the proposed algorithm, using the torques of the active rotary joints set the base plate, the passive linear joints set the each joint can be transformed.

However, these realized transformations don't match the desired transformation of the passive linear joints. This is because the influence the modeling error of the mechanism, for example friction force of each joints, the link mass and so on, and the time-lag of the response of the lock systems based air pressure and so on. Consequently, we need to perform the precise dynamic parameters calibration and the feed back control using the value which can be obtained with the linear encoder sensor set the passive linear joints, which are our future works.

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