Detecting Method of Friction Force on Linear Actuators of a Parallel Manipulator Based on the Gravitational Force

Haeng Bong Shin

Dept. of Mechanical Design, Graduate School,
Kyungnam University,
Masan, Gyeongnam, 631-701, Korea

Se Han Lee

School of Mechanical and Automation Eng.,
Kyungnam University,
Masan, Gyeongnam, 631-701, Korea

Abstract

Parallel manipulators have been used to a variety of applications, including the motion simulators and mechanism for precise machining. A Stewart-Gough type parallel manipulator is composed of six linear joints, which have wider contact areas than revolute ones, so linear joints are more affected by frictional force. First, the reference trajectories are computed from the model of the parallel manipulator assuming that it is subject to only the gravitational force and no friction exists. In the actual operation where friction exists, the control inputs, which correspond to the friction forces, are obtained by forcing the actual joint variables to follow these trajectories by proper control. It is shown that control performance can be improved when the friction compensation based on this information is added to the controller for position control of the moving plate of a parallel manipulator.

1. Introduction

Recently, there are carried out so many parallel manipulator applications for machining machine, motion simulator [1,2] and so on. In particular, a conventional Stewart-Gough type parallel manipulator has a good rigidity ration over the weight since it uses mainly linear actuators where bending effect does not apply. In addition, the errors from each actuator are not accumulated and distributed since the actuators are arranged in parallel with closed loop form. Thanks to the characteristics, there is introduced the parallel manipulator to applications of handling tool and carriage in the machining machine which requires high rigidity.

Generally, on the contrary to the merits above, there is a deficit of small workspace since the actuators have limited stroke and are arranged in parallel with closed loop form and they can interfere with themselves. In addition, in case of the conventional Stewart-Gough platform, there is significant friction force on each actuator. A linear type actuator has wider contacting surface than a revolute one and has more friction problem. Meanwhile, ball-screw device for converting rotation to translation motion may have an intentional pre-stress because pre-stress can eliminate backlash and any other mechanical alignment error. The pre-stress can cause more friction problem. In particular, the conventional Stewart-Gough platform has 6 identical actuators, and the actuators are required to be as more identical as possible. However, it is impossible that they are all identical perfectly. Friction force on each actuator is expected to be detected and is compensated for better control performance.

As a method for detecting friction force, when a constant force is applied to the destination, the resultant acceleration can tell us how much friction force is. That is hard to be performed due to a calibration problem because it is hard to apply an exactly scaled force to the destination. The gravitational force can be a candidate for that because the gravitational force can be easily assumed as constant force. Actually, the gravitational force is most likely a constant and even free cost.

If the gravitational force is applied to an ideal parallel manipulator without any friction effect, the end-effector of the parallel manipulator falls down freely according to the Newton’s law. Actually, the end-effector falls down slowly than expected or even stops with the friction force on each actuator. When the actuators are controlled in order to make the end-effector follow the ideal free fall trajectory, the control input for the actuators can be assumed as the efforts for compensating the friction force. For better tracking performance, the control efforts corresponding to actuator’s position can be stored and recalled for controlling the end-effector to follow an arbitrary trajectory.

In this study, Chapter 2 describes characteristics of a conventional Stewart-Gough platform, Chapter 3 describes a method for detecting friction force, Chapter 4 shows the validity of the method with experimental results, Chapter 5 makes conclusions finally.

2. Stewart-Gough parallel manipulator

Stewart-Gough has two plates, moving plate (end-effector) and fixed plate that are connected with 6 linear actuators in parallel. The end-effector has 6 dof (degree of freedoms) with 3 dof of position and 3 dot of orientation [4]. A parallel manipulator like the

Stewart-Gough platform, has opposite characteristics to the a serial one that inverse kinematics for the parallel is easier than that for a serial one, forward kinematics of the parallel one is more difficult than that of a serial one and does not even have analytical solutions. In addition, it is possible to perform accurate control since the actuation structure is closed form and the error on each actuator is distributed and it is also to obtain high rigidity over lightweight since the actuators run stress and tensional direction without bending. Meanwhile the end-effector workspace is limited since the actuator's stroke is limited and has closed form structure.

Meanwhile as a parallel manipulator uses a linear type actuator and the contacting surface of the linear type actuator becomes wider than a revolute type actuator, friction force effect of the parallel manipulator is significantly increasing. In addition, ball-screw device for converting rotation to translation motion may have an intentional pre-stress because pre-stress can eliminate backlash and any other mechanical error. The pre-stress can cause more friction problem. As a result, the parallel manipulator falls down slowly or even is fixed due to the friction force without any actuation force.

Figure 1 shows a conventional Stewart-Gough platform built in the study. As an experimental setup, the Stewart-Gough platform uses a ball-screw device at which a high pre-stress (75kgf) is applied. Due to the friction force, the end-effector of the parallel manipulator is fixed. It is well known that friction force is a negative factor for control performance. If the friction force can be detected exactly and compensated, the control performance will be improved.

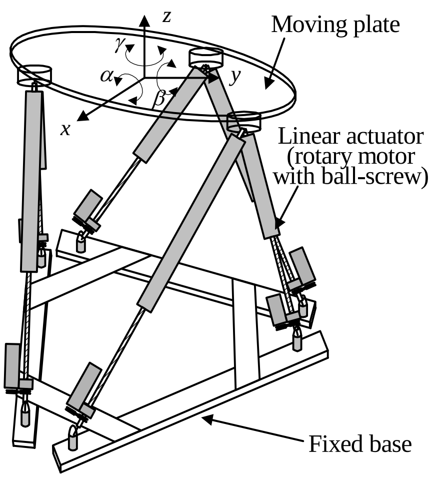


Fig. 1 Stewart-Gough type parallel manipulator.

3. Friction force detection using gravitational force

As a method for detecting friction force on a manipulator, when and external force magnitude applied to a manipulator is increasing, a force corresponding to the moment at where the manipulator begins to move can be assumed a friction force on the manipulator. This method is very simple, however, it is most likely impossible to generate force exactly and it is required additional equipment for generating force. In this study, the gravitational force that always exists everywhere manipulator and even free cost will be used for detecting friction force.

Dynamic equations for a multi-degree manipulator are described as a non-linear form equation as following

$$\mathbf{J}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{N}(\mathbf{q},\dot{\mathbf{q}}) + \mathbf{G}(\mathbf{q}) = \tau \qquad (1)$$

where $\mathbf{q}\in R^n$ denotes joint variables on the manipulator (n stands for the numbers of the joints), $\mathbf{J}(\mathbf{q})$ denotes moment of inertia, $\mathbf{N}(\mathbf{q},\dot{\mathbf{q}})$ denotes non-linear term corresponding to centripetal and Coliolis force, $\mathbf{G}(\mathbf{q})$ denotes gravitational force term, and τ denotes external torques. The gravitational force term $\mathbf{G}(\mathbf{q})$ in (1) is dependent on the configurations, $\mathbf{q}$ and is independent of initial velocity or acceleration. If there is no external force, $\tau = \mathbf{0}$, (1) becomes

$$\mathbf{J}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{N}(\mathbf{q},\dot{\mathbf{q}}) = -\mathbf{G}(\mathbf{q}) \neq 0 \qquad (2)$$

Only the gravitational force in (2) is applied to the manipulator. In case of a serial manipulator with a revolute type actuator that has less friction force than parallel one, the end-effector of the serial one falls down slowly along the gravitational direction since the friction force cancels some part of the gravitational force. If there is no friction force on each actuator, the end-effector falls down freely. By solving (2), the joint variable, $\mathbf{q}_g$ corresponding to the free fall trajectory can be obtained.

Here is considering a case with friction force. If the friction force is bigger than the external one, the friction force is the same as the applied external force and the external force is canceled exactly. As described above, friction force on the parallel manipulator is relatively large and the external force (gravitational force in this case) fades away due to the friction force. As a result, (2) becomes

$$\mathbf{J}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{N}(\mathbf{q},\dot{\mathbf{q}}) = -\mathbf{G}(\mathbf{q}) + \mathbf{F}_{\text{friction}}(\dot{\mathbf{q}}/|\dot{\mathbf{q}}|) = 0 \qquad (3)$$

where $\mathbf{F}_{\text{friction}}(\dot{\mathbf{q}}/|\dot{\mathbf{q}}|)$ denotes friction force acting opposite direction of the manipulator.

As if there is controlled the manipulator following the free fall trajectory, the control efforts to each actuator are the same as friction force on each actuator. The control input $\mathbf{u}$ is carefully adjusted in order for the joint variable $\mathbf{q}$ to follow the pre-computed trajectory $\mathbf{q}_g$.

$$\begin{aligned}&\mathbf{J}(\mathbf{q_g})\ddot{\mathbf{q}}_\mathbf{g} + \mathbf{N}(\mathbf{q_g},\dot{\mathbf{q}}_\mathbf{g})\dot{\mathbf{q}}_\mathbf{g} \\ &\quad = -\mathbf{G}(\mathbf{q_g}) + \mathbf{F}_{\text{friction}}(\dot{\mathbf{q}}_\mathbf{g}/|\dot{\mathbf{q}}_g|) + \mathbf{u}\end{aligned} \qquad (4)$$

By letting the left side of (2) be the left one of (4), the following is satisfied

$$\mathbf{F}_{\text{friction}}(\dot{\mathbf{q}}_\mathbf{g}/|\dot{\mathbf{q}}_\mathbf{g}|) + \mathbf{u} = 0 \qquad (5)$$

As (5) shows that the control input, $\mathbf{u}$, cancels the friction force, $\mathbf{F}_{\text{friction}}(\dot{\mathbf{q}}/|\dot{\mathbf{q}}|)$, the control input will be corresponding to the friction force. A friction force $\mathbf{F}_{\text{friction}}(\mathbf{q})$ corresponding to joint variable $\mathbf{q}$ can be obtained. Base on that friction force, the friction force can be added into control effort as following and better control performance is expected.

$$\mathbf{u}_{\text{enhanced}} = \mathbf{u}_{\text{nominal}} + \mathbf{F}_{\text{friction}}(\mathbf{q}) \qquad (6)$$

4. Experiments

A Stewart-Gough platform is constructed for the study. It consists of 6 linear actuators with 400W class BLDC (BrushLess DC) motor and ball-screw device. Detail specifications are on the following Table 1, and the experimental setup is shown in Fig. 2. A computation burden for the controlling the parallel manipulator is very significant. The controller consists of 2 parts, high level and low level controller. The high level controller, PC takes role of kinematics computation while the low level controller, TMS320C31 DSP takes role of controlling each actuator.

Table 1 Workspace of the developed parallel manipulator.

Items	Ranges
Pay Load	200kg
X-translation	±0.2m
Y-translation	±0.2m
Z-translation	±0.1m
Roll	±25^{o}
Pitch	±25^{o}
Yaw	±30^{o}

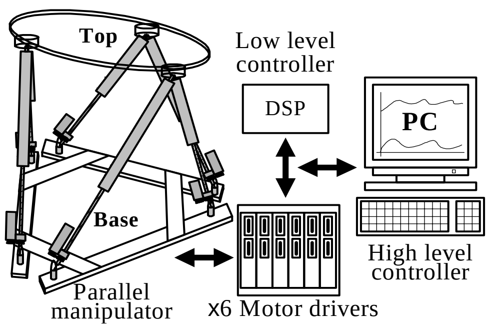


Fig. 2 Schematic of experimental setup.

4.1 Friction force detection

Before performing the experiments, inverse dynamics of the parallel manipulator is computed under external force condition of gravitational force. As the external force is applied vertically to the parallel manipulator and the configuration of the manipulator is symmetric, every trajectory of each actuator is the same. For that reason, only one trajectory of the actuator and vertical trajectory of the end-effector are shown in Fig. 3.

Each actuator connected to the real parallel manipulator is controlled to follow the pre-computed free fall trajectory and the control efforts are shown in Fig. 4. They are corresponding to forces overcoming the friction forces. There are shown friction forces of 250 N average. They show that the biggest friction is on 3rd actuator and the smallest one is on 4th actuator.

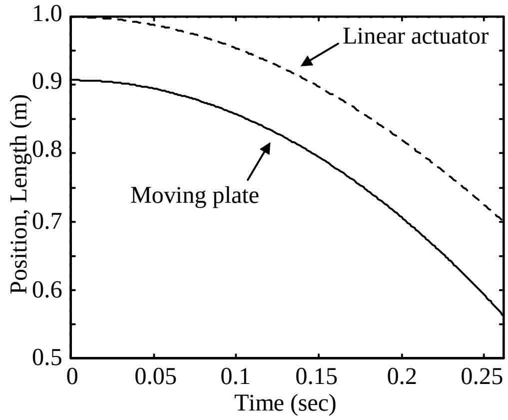


Fig. 3 Trajectories of linear actuator and moving plate under gravitational force alone.

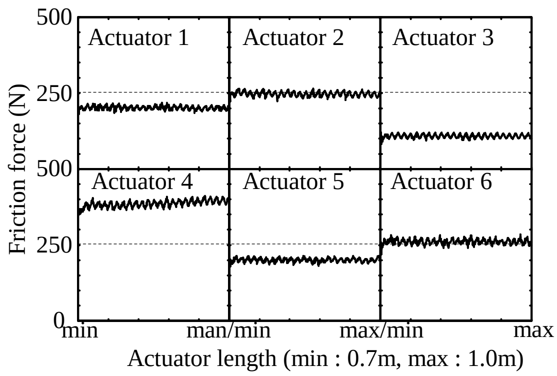


Fig. 4 Control efforts of six linear actuators which follow the ideal trajectories.

As a result of detecting the friction force of the parallel manipulator, the resultant shows that the friction force on each actuator is different with each other though the configuration of the parallel manipulator is symmetric. The reason is that all the parts for the parallel manipulator is not ideally uniform and fabricated. If the same gain is applied to the each controller without considering each actuator's property, it is hard to expect to obtain uniform control performance.

4.2 Friction compensation

In order to check the validity of the detected friction force, the friction force profiles are applied to the controller. There is introduced a simple PID controller for showing potential of the friction force compensation.

$$\mathbf{u} = \mathbf{K}_P(\mathbf{q}_{\text{ref}} - \mathbf{q}) + \mathbf{K}_I \int (\mathbf{q}_{\text{ref}} - \mathbf{q})dt + \mathbf{K}_D(\dot{\mathbf{q}}_{\text{ref}} - \dot{\mathbf{q}}) \quad (7)$$

where $\mathbf{K}_P, \mathbf{K}_I, \mathbf{K}_D, \mathbf{q}_{\text{ref}}$ denotes proportional gains, integral gains for compensating the gravity, derivative gains, and reference trajectory respectively. The detected friction force is added into the control effort finally shown in (6).

Figure 5 shows 2 cases; one is that only feedback controller takes role of compensating property of each actuator (assuming that mechanical property and friction force on each actuator is the same), the other is that pre-computed friction force is added into the control input. In order for all 6 actuators to move simultaneously, a circular trajectory is introduced for reference trajectory. Figure 5 shows that the tracking performance for friction compensation with feedforwarding pre-computed friction force to the control input along the joint variable **q**, is better than that for no friction compensation. In case of no friction compensation, the reason for the irregular tracking pattern is that each error on the actuator is represented in end-effector non-linearly due to the non-linear kinematics of the manipulator.

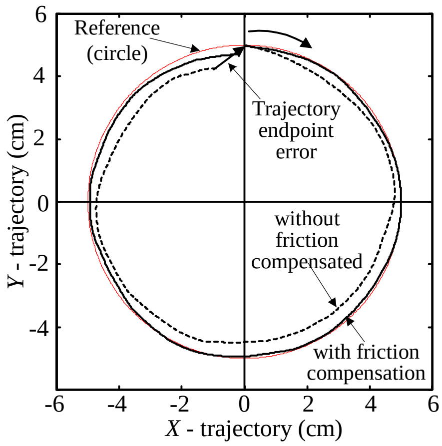
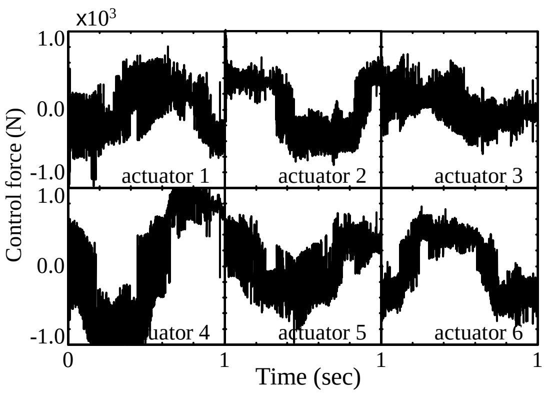
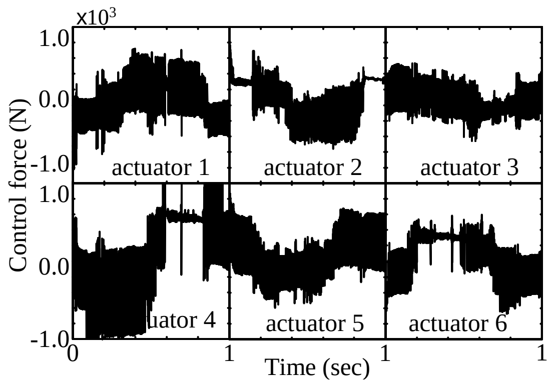


Fig. 5 Tracking performance of the moving plate following reference circular trajectory during the PID control without and with friction compensation.

Figure 6 shows control inputs of both cases. Though the outlines of both cases are similar to each other, in case of friction compensation, the control input difference between max. and min. is decreasing little bit. The reason is expected that the integral part increases the control input to overcome the friction force.



(a)



(b)

Fig. 6 Control inputs for (a) the controller without friction compensation, and (b) the controller with friction compensation.

5. Conclusions

There is introduced a friction force detection scheme for a parallel manipulator in this study. This scheme uses the gravitational force for free cost and makes the compensation algorithm be only a part of control algorithm without any additional equipment. Because the scheme is included in the controller as a part of algorithm, the friction detection scheme can be carried out at every initial action or at any time for the request. The possibility to carry out the friction detection at every initializing becomes a very significant merit when the friction force is always subject to change according to environmental temperature, humidity, and operating conditions.

By performing experiment of friction compensation with the detected friction force, the validity of the friction detection method is presented. Since the friction compensation method can be implemented into main controller with feedforward form, it does not require additional complicated computation burden.

Acknowledgements

This research was supported by the **N**ew **U**niversity for **R**egional **I**nnovation program of the Ministry of Education & Human Resources Development (NURI MECHANO 21).

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