Huge-Object Manipulation in Space by Vehicle-Type Robots*

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Previous studies on space robots have assumed a relatively small object as the manipulated target, but in space, a target object can be relatively large, e. g., a space station or a solar-powered satellite. In these cases, manipulation by several vehicle-type robots or vehicles, hereafter, which have thrust engines is superior to that by arms mounted on spacecraft. In manipulation by vehicles, fuel consumption in a thrust engine is related to the norm of force generated by the vehicle. The norm of the force depends on the positions of contact points. Therefore, contact points of the vehicles are important in view of the fuel consumption. In this paper, the optimal contact points are defined as the points which minimize the norm of force needed for the acceleration of the target object or maximize DMM (dynamic manipulability margin) according to the nature of the task. Experiments to verify the validity of this optimal contact points determination method will also be shown.

Key Words: Space Robot, Manipulation by Vehicles, Cooperation of Multiple Robots, Optimal Contact Points, Norm of Force, Dynamic Manipulability Margin

1. Introduction

Some projects, e.g., construction of a solar-powered satellite (SPS) or space colony, are proposed. Asteroids are expected to be used as resources for construction in these projects. Because of such unfavorable factors as weightlessness and radiation, space is an unsuitable environment for humans. Therefore, it is essential to use space robots in these projects, instead of people.

Recently, flexible arms and spacecrafts with arms have been actively studied with an eye to space manipulation⁽¹⁾⁻⁽⁵⁾. Such research has so far assumed a relatively small object to be the target of manipulation, such as in recovery of damaged satellites or in construction of a space station. On the other hand, in the case of moving or assembling a huge target object

Fig. 1 Manipulation of a huge object by arms (a) and by vehicle-type robots (b)

such as the SPS, manipulation by several vehicle-type robots which have thrust engines (Fig. 1(b)) is superior to that by arms mounted on spacecrafts (Fig. 1(a)) for the following reasons.

(1) Only the thrust engine can be used as a large-power actuator.

(2) Since connections which transmit large moment between a target object and an end effector are impossible in view of the strength, the connection is limited to the point contact which transmits only force. Therefore an arm which has more than 3 degrees of freedom is not effective.

In this paper, we propose a method of

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manipulation of large objects by vehicle-type robots (hereafter simply called 'vehicle') as follows. Each vehicle functions as a 3-DOF force generator by means of the thrust engine fixed on it. It applies contact force through friction by pushing the object. Then the desired acceleration is supplied to the object by the contact force of all vehicles, and manipulation is realized. Here, manipulation includes not only the transfer of the object from one place to another, but also the object assembly task.

From the viewpoint of manipulated object, the role of the vehicles is similar to that of the finger tips in multifinger manipulation, except for the following significant differences.

(1) Fuel consumption in a thrust engine is important due to the limitation of fuel. Thus it is necessary to consider minimization of fuel consumption during manipulation.

(2) In the case of multifingers, contact points are limited by kinematic constraints, but in the case of vehicles, contact points can be selected freely on the surface of a target object.

(3) The number of vehicles can be easily increased or decreased as the need arises.

In manipulation by vehicles, fuel consumption is related to the force that the vehicle applies to the object. However, the force which supplies acceleration to the object depends mainly on the position of the contact points. Moreover, accelerations of the object are also related to the position of contact points. Therefore we focus on how to select optimal contact points for manipulation, and propose two indices for determining optimal contact points: "norm of contact force" which indicates how efficiently a target object is accelerated, and "dynamic manipulability margin" (/DMM) which indicates the variability of target object acceleration from the desired acceleration.

In this paper, we outline the forms of manipulation by a vehicle and the forms of construction of the vehicle-type robot. The method of determining the optimal contact points according to the type of manipulation task is discussed. The experimental system for simulating the manipulation on earth and the result of a verification experiment are also shown.

2. Manipulation and Vehicle-Type Robot

In this paper, the following are assumed.

(1) Point contact occurs between the object and vehicle.

(2) For moving and generating force, a main thrust engine is fixed on each vehicle. Some auxiliary thrust engines are fixed to the sides of the vehicle for control of vehicle position.

Fig. 2 Pushing object with vehicle: (a) moment is produced during pushing by vehicle with a movable thrust engine; (b) pushing by vehicle in which thrust passes through vehicle's center of mass and contact point

(3) By means of static friction, contact force is transferred to the object from the thrust of the main engine of the vehicle. The object is accelerated to a desired velocity by total of all contact forces.

For the reason illustrated in Fig. 2, the vehicle which we propose is one which has a 3DOF control moment gyro (CMG) for orientation control. In this case, by controlling vehicle orientation, the direction of the contact force is controlled and no excess moment around the center of mass is produced (Fig. 2 (b)).

3. Mechanics of Manipulation

3.1 Equation of motion

The equation of motion of a target object is formulated as follows.

$$A_0 \ddot{\mathbf{q}} = \mathbf{E}_0^T \mathbf{F} \quad (1)$$

$$\ddot{\mathbf{q}} \triangleq [{}^B \ddot{\mathbf{s}}_0^T, {}^0 \ddot{\boldsymbol{\omega}}_0^T]^T, {}^0 \ddot{\boldsymbol{\omega}}_0 \triangleq {}^0 \dot{\boldsymbol{\omega}}_0 + {}^0 I_0^{-1} \boldsymbol{\omega}_0 \times ({}^0 I_0 \boldsymbol{\omega}_0)$$

$$\mathbf{F} \triangleq [{}^0 \mathbf{f}_1^T, \dots, {}^0 \mathbf{f}_N^T]^T$$

${}^B \mathbf{s}_0 \in R^3$: position of center of mass of the object

${}^0 \boldsymbol{\omega}_0 \in R^3$: angular velocity of the object

${}^0 \mathbf{f}_i \in R^3$: contact force supplied by i th vehicle

N : total number of vehicles

A_0 : inertia matrix

$\mathbf{E}_0^T$: constraint matrix

Leading superscripts of vectors B and o refer to inertial base frame and coordinate frame attached to the center of mass of object, respectively. Subscript o refers to the object. Subscript $i=1 \sim N$ refers to individual vehicles.

There are the constraints of the norm of the contact force determined by the maximum power of the thrust engine.

$$|\mathbf{f}_i| \leq f_i^{\max} \quad (2)$$

The desired maximum accelerations, $\dot{\mathbf{s}}_0^{\max}$, $\dot{\boldsymbol{\omega}}_0^{\max}$, are determined for ${}^B \dot{\mathbf{s}}_0$, ${}^0 \dot{\boldsymbol{\omega}}_0$. Normalized acceleration $\ddot{\mathbf{q}}$ and normalized force $\hat{\mathbf{F}}$ are formulated as follows.

$$\ddot{\mathbf{q}} = T_a \ddot{\mathbf{q}} \quad (3)$$

$$T_a \triangleq \text{diag}[1/\dot{\mathbf{s}}_0^{\max}, \dots, 1/{}^0 \dot{\boldsymbol{\omega}}_0^{\max}, \dots]$$

$$\hat{\mathbf{F}} = T_f \mathbf{F} \quad (4)$$

$$\mathbf{T}_f \triangleq \text{diag}[1/f_1^{\max}, \dots, 1/f_N^{\max}, \dots]$$

Then, Eqs. (1) and (2) can be normalized as follows.

$$\ddot{\mathbf{q}} = \hat{\mathbf{J}} \hat{\mathbf{F}}, \quad \hat{\mathbf{J}} \triangleq \mathbf{T}_a \mathbf{A}_0^{-1} \mathbf{E}_0^T \mathbf{T}_f^{-1} \quad (5)$$

$$|\hat{\mathbf{f}}_i| \leq 1 \quad (6)$$

We call the normalized acceleration $\ddot{\mathbf{q}}$ and the normalized contact force $\hat{\mathbf{F}}$, simply, acceleration and contact force, respectively.

3.2 Statics friction constraint

When the position of the contact point i is given, the contact force $\hat{\mathbf{f}}_i$ must satisfy Eqs. (2) and (5) for $\ddot{\mathbf{q}}(t)$. The following friction constraint must also be satisfied:

$$\mathbf{n}_i^T \hat{\mathbf{f}}_i \geq \eta_i |\hat{\mathbf{f}}_i|, \quad (7)$$

where $\mathbf{n}_i$ is the normal vector at the contact point, μ_i is the maximum static friction coefficient, and $\eta_i = 1/\sqrt{1+\mu_i^2}$.

4. Norm of Contact Force

Up to now, research on object manipulation has focused on the multifinger and the multiarm. Regarding the manipulation from these viewpoints, solving the grasping force is the main problem. Hanafusa et al.⁽⁶⁾ defined the norm of the grasping force of three-fingered hands as the area of a triangle formed by internal force vectors, and proposed a performance criterion to determine the optimal grasping force based on it under the static friction constraints. Kerr and Roth⁽⁷⁾ approximated the frictional constraints by linear constraints, and proposed that the optimal internal force for the linear constraints and the joint torque constraints can be computed by a linear programming method. Nakamura et al.⁽⁸⁾ proposed optimal grasp in which the minimizing norm of grasping force can be solved by the nonlinear programming method. Although determining the position of contact of the fingertip is one of the main problems, Hanafusa and Asada⁽⁹⁾ suggested grasping of an object at the position where the potential energy of the elastic fingers is minimized. For grasping of a planar polygonal object by a multifingered hand, Omata⁽¹⁰⁾ proposed that the problem of determining the optimal fingertip position can be formulated as an optimization problem wherein fingertips have been fixed at special points.

Here, we refer to the research of Nakamura et al.⁽⁸⁾, and discuss the selection of contact points according to the norm of force.

4.1 Optimal contact force

The optimal contact force $\hat{\mathbf{F}}^{ocf}$ is defined as the contact force which gives the minimum norm satisfying Eqs. (5), (6) and (7).

$$|\hat{\mathbf{F}}^{ocf}|^2 = \min(|\hat{\mathbf{F}}|^2) = \min\left(\sum_{i=1}^N |\hat{\mathbf{f}}_i|^2\right) \quad (8)$$

Nakamura et al. proposed the application of the non-linear programming method to obtain the optimal contact force⁽⁸⁾. This method provides a solution to the manipulation problem, but has the weak point that it is very expensive in terms of computational time and is consequently unsuitable for real-time operation with currently available computer hardware. However, by approximating the friction cone as a polygonal pyramid, the problem of solving the optimal contact force can be formulated as a quadratic programming problem which can be computed efficiently. This method is adopted in our work.

4.2 Contact points giving the minimum contact force

When the acceleration of the object is $\ddot{\mathbf{q}}$, the norm of the optimal contact force $|\hat{\mathbf{F}}^{ocf}|$ mainly depends on the positions of contact points. Therefore, it is necessary to determine the contact points which give the minimum $|\hat{\mathbf{F}}^{ocf}|$ in order to minimize fuel consumption.

The problem of determining the contact points analytically has been discussed in another paper⁽¹⁰⁾. We here adopt the computational method instead. That is, we divide the surface of a target object into n parts and compare the values of $|\hat{\mathbf{F}}^{ocf}|$ in the possible pairs of contact points. This method requires computations for nC_N pairs, but it has the advantage that other indices also can be applied simultaneously, as described in section 5.

For example, we consider a 2D planar ellipse and define 20 candidates for contact points, as shown in Fig. 3. The results of calculation of $|\hat{\mathbf{F}}^{ocf}|$ for three accelerations, moving in the directions of x and y axes and rotating around the z axis, are shown in Fig. 4. Among the ${}_{20}C_2$ pairs of contact points, three pairs which give smaller $|\hat{\mathbf{F}}^{ocf}|$ are shown. In Fig. 4, the broken arrows (both straight and curved) in the center of the object, dotted arrows and solid arrows at the contact point indicate the desired acceleration of the target object, the normal vector at the contact point, and the force applied by the vehicle, respectively. We can see that there are pairs which give identical values of $|\hat{\mathbf{F}}^{ocf}|$ in Fig. 4(b). In this case, another index must be introduced to determine the contact

Fig. 3 Division of the surface of a target object and candidates of contact points. Each arrow shows the normal vector at each contact point.

Fig. 4 The norm of the force and the dynamic manipulability margin at various contact points for the specified acceleration ($\mu_i = \tan \frac{\pi}{3}$)

points.

5. Contact Points and DMM

The normalized dynamic equation of a manipulator is formulated as

$$\ddot{\mathbf{q}} = \mathbf{J} \hat{\mathbf{r}}. \quad (9)$$

When joint torque input $\hat{\mathbf{r}}$ is constrained by $|\hat{\mathbf{r}}_i| \leq 1$, the set of realizable accelerations $\ddot{\mathbf{q}}$ is an ellipsoid. Yoshikawa called it dynamic manipulability ellipsoid (/DME), and used the volume and the shortest minor axis of this ellipsoid for the measurement of manipulability, which is useful in manipulator design⁽¹¹⁾. Moreover, the evaluation of dynamic dexterity which considers the probability distribution of acceleration, has been proposed⁽¹²⁾. The relationship between internal force and the manipulability polyhedron when the object is restricted by the hands of a multiarm robot during manipulation has also been discussed⁽¹³⁾.

For DME, we define an index which shows 'how much the target object can be manipulated under the static frictional constraint,' and use it in determining contact points.

5.1 Constraints separating method in DMB calculation

The set of accelerations $\ddot{\mathbf{q}}$ obtained under the constraints of the contact force $\hat{\mathbf{F}}$, Eqs. (6) and (7), indicates the realizable acceleration of the target object at the contact points. We call this set of $\ddot{\mathbf{q}}$ the dynamic manipulability body (DMB).

In general, it is difficult to obtain DMB analyti-

cally because the shape of the DMB is very complicated due to the existence of the static friction constraint (7). However, it is possible to obtain an approximate DMB by calculating whether $\hat{\mathbf{F}}^{ocf}$ exists for each point in the acceleration space $\ddot{\mathbf{q}} \triangleq (\ddot{x}, \ddot{y}, \ddot{z}, \ddot{\omega}_x, \ddot{\omega}_y, \ddot{\omega}_z)^T$. However, this method requires an excessive amount of computation. Moreover, it is difficult to distinguish whether the point on the boundary surface of the DMB is a result of constraints (6) or (7) of the contact force. Therefore, we propose a method which separates the two constraints, (6) and (7), by using the spherical coordinate, which also decreases the amount of computation.

In the remainder of this section, we consider 2D planar motion, but it is easy to expand this method to 3D motion.

In $\ddot{\mathbf{q}}(\ddot{x}, \ddot{y}, \ddot{\omega}_z)$ space, we introduce the following spherical coordinates:

$$\begin{aligned} \ddot{x} &= r \cos \varphi \cos \theta, \ddot{y} = r \cos \varphi \sin \theta, \ddot{\omega}_z = r \sin \varphi \\ &-\pi/2 \leq \varphi \leq \pi/2, -\pi \leq \theta \leq \pi. \end{aligned} \quad (10)$$

In Eq. (10), r is the amount of acceleration. We consider a sphere with a very small radius $r_1 (\ll 1)$ which makes the force norm constraint (6) negligible. On its surface, we consider the points at which $\hat{\mathbf{F}}^{ocf}$ satisfies the equation of motion (5) under the friction constraint (7). Then, the set of these points is a cross section of the DMB on the surface of a sphere of radius r_1 . This cross section is independent of constraint (6). We call it MMR (minute manipulable region).

In Eq. (5), we let $\hat{\mathbf{F}}_1^{ocf}$ be the optimal contact force for $\ddot{\mathbf{q}} \triangleq \ddot{\mathbf{q}}(\theta, \varphi, r_1)$ in MMR. Then $k\hat{\mathbf{F}}_1^{ocf} (k > 0)$ satisfies the friction constraint (7) and is the optimal contact force for $k\ddot{\mathbf{q}}_1$.

$$\hat{\mathbf{F}}_k^{ocf} = k\hat{\mathbf{F}}_1^{ocf} \quad (11)$$

Therefore, we can check whether $\ddot{\mathbf{q}}_k \triangleq \ddot{\mathbf{q}}(\theta, \varphi, kr_1) = k\ddot{\mathbf{q}}_1$ is inside of DMB by checking whether $k\hat{\mathbf{F}}_1^{ocf}$ satisfies the force norm constraint (6). The boundary of DMB in the radial direction is determined by k_{limit} , the maximum value of k :

$$k_{limit} = 1 / \max_i (|\hat{\mathbf{F}}_{1i}^{ocf}|). \quad (12)$$

This relation means that, using spherical coordinates, the amount of computation of DMB is decreased by decreasing the dimension of the calculated acceleration space from 3 (the dimension of $(\ddot{x}, \ddot{y}, \ddot{\omega}_z)^T$) to 2 (that of $(\theta, \varphi)^T$).

The result of DMB calculated for the examples in Fig. 4 is shown in Fig. 5. It is easily established from Fig. 5 that volume and shape of DMB are very different when the position of contact points is different. From the aspect of control, it is better that DMB be as large as possible because the set of

Fig. 5 The shapes of dynamic manipulability body (DMB) at various contact points for the specified acceleration ($\mu_i = \tan \frac{\pi}{3}$)

realizable accelerations would be large. However, when the desired acceleration of the object is given, an index such as 'dynamic manipulability' which only considers the volume of DMB is not suitable. Manipulability around the desired acceleration is, therefore, more important.

5.2 Dynamic manipulability margin (DMM)

In view of control, it is preferable that the range of acceleration which can be applied to a target object around the desired acceleration be as wide as possible. We define DMM (dynamic manipulability margin) as the shortest distance from the desired acceleration $\ddot{\mathbf{q}}_d$ to the surface of DMB and use it as an index which represents how widely a target object can be accelerated around the desired acceleration.

When considering 2D planar motion, DMM is formulated using the spherical coordinates defined in section 5.1 as follows:

$$\text{DMM} \triangleq \min_{\theta, \varphi} |\ddot{\mathbf{q}}(\theta, \varphi, kr_1) - \ddot{\mathbf{q}}_d| \quad (13)$$

$$k = \begin{cases} k_{\text{limit}}, & \text{if } \ddot{\mathbf{q}}(\theta, \varphi, r_1) \in \text{MMR} \\ 0, & \text{otherwise.} \end{cases}$$

DMM can be obtained by calculating all points on a surface of the sphere of radius r_1 . (Note that the amount of computation has been decreased because the dimension of the calculated acceleration space has been decreased to 2 here.)

Here, we compare DMM with the dynamic manipulability, defined by Yoshikawa⁽¹¹⁾ or the one in

multiarm coordinative manipulation proposed in Ref. (13). Unlike the 'dynamic manipulability' which shows the status of all realizable accelerations when a manipulator is at a certain attitude, the 'dynamic manipulability margin (DMM)' shows the status of the local space around the desired acceleration. They are also different in that the static frictional constraint is considered in DMM.

The calculation result of DMM is shown Fig. 4. When comparing three pairs of contact points in Fig. 4(b), the norms of force $|\hat{\mathbf{F}}|$ are equal and cp (4, 16) is most desirable because it gives the maximum DMM. Among several pairs of contact points in which the norms of force are equal, we can define the optimal contact points as those which give the maximum DMM. However, in the case that the norms of force $|\hat{\mathbf{F}}|$ are not equal, such as the case shown in Fig. 4(a), how we combine two indices, $|\hat{\mathbf{F}}|$ and DMM, in the optimal contact point decision remains a problem.

6. Optimization of Contact Points

6.1 Manipulation task

The manipulation task carried out by vehicles can be divided into the following two main parts (Fig. 6):

- transferring a target object between orbits,
- assembling a target object at the desired position.

Both tasks involve the same mechanics model but are different in terms of the target object control and the optimization of contact points. In the construction of large space structures, transfer between orbits means transfer of basic structures for use in the construction of large space structures to geostationary earth orbit (GEO) from low earth orbit (LEO) using vehicles. Such transferring always takes place over a long time and a long distance. Therefore minimizing fuel consumption at each moment of manipulation is very important to minimize fuel consumption of the total manipulation task. In view of control, if the final position can be achieved, accuracy of the path taken during each moment will not be important.

Assembling space structures means setting a basic structure in the correct position and orientation with respect to other basic structures or other space structures under construction, and joining them together. In this case, for the reason that all objects are floating in space, positions and orientations of the basic structures and the space structures under construction must be controlled very carefully. Moreover, since the huge space structure is flexible, approach velocity and compliance of each direction in manipulation must be controlled to avoid shock.

6.2 Optimal contact points

The two indices, minimum contact force and maximum DMM, should not be the same in both the

Fig. 6 Transfer and assembly: two manipulation tasks by vehicles in constructing a solar-powered satellite

physical meaning of optimization and the optimization result. For this reason, these two indices must be put to proper use according to the nature of the manipulation task.

In the case of object transfer in which minimization of fuel consumption is more important, it is reasonable that the optimal contact points be defined as those where the norm of the contact force is minimum, rather than considering the DMM, to achieve the final desired position.

During the manipulation, natural disturbances, such as the infinitesimal force of gravity from planets or the pressure of radiation from the sun, exist. Disturbance due to collision between assembled objects also exists. However, unlike on earth where there is air resistance or frictional resistance, there is no resistance force which reduces disturbances in space. Therefore in object assembly, control stability and the ability of convergence from error caused by disturbances are so important that the optimal contact points are defined as points where DMM is maximum.

In conclusion, for transfer and assembly in space, the optimal contact points are defined by the two indices, norm of contact force and DMM (Fig. 7). A simulation of continuous manipulation with these two indices has been shown in Ref. (14).

7. Verification Experiment

In section 6.2, the optimal contact points are determined based on the two indices. This procedure is verified through experiments with a 2DOF experimental system (Fig. 8) in which vehicles robots and

Fig. 7 Optimization of contact points according to task types

the target object float above a $1\text{m} \times 1\text{m}$ air-bearing table.

7.1 Scheme of verification experiment

Basically, it is reasonable to consider that the transfer of an object involves high-acceleration motion and that assembly involves low-acceleration motion in space. Here, contact force and DMM are shown in Fig. 9 for combinations of two specific contact points and two accelerations (the static friction angle is 15 degrees). The accelerations shown in Fig. 9 are normalized, with maximum and minimum being $0.125(0.00258 \text{ m/s}^2)$ and $0.05(0.00103 \text{ m/s}^2)$,

Fig. 8 System for manipulation by vehicle robot

Fig. 10 Experimental result (contact points: (A) acceleration: high)

respectively.

According to the results in Fig. 9, binding type (A) has a large contact force because a large internal force acts on the object. Conversely, nonbinding type (B) only has a small contact force because internal force is zero. The DMM is large in (B) at high acceleration and in (A) at low acceleration.

In the experiment, the norm of contact force can be shown by that of the thrust of each vehicle. However, there is no index to indicate the magnitude of DMM directly. Thus in this experiment, initial errors in position and orientation of the object are added, and the ability to restore motion along the desired path is used to distinguish the magnitude of

	$\ddot{q} = (0.0, 0.125, 0.0)$	$\ddot{q} = (0.0, 0.05, 0.0)$
(A)	 $DMM = 0.074$ $\ F\ = 0.137$	 $DMM = 0.116$ $\ F\ = 0.055$
(B)	 $DMM = 0.125$ $\ F\ = 0.035$	 $DMM = 0.050$ $\ F\ = 0.014$

Fig. 9 Calculation results of the contact force and the DMM for desired accelerations and position of contact points for the verification experiments

Fig. 11 Experimental results (contact points: (B) acceleration: high)

DMM.

A $0.6 \text{ m} \times 0.4 \text{ m}$ rectangular metal plate is used as the object which weighs 19.4 kg, 13 times the weight of a vehicle. Inertial moment around the z axis at the center of mass of the object is 0.84 kgm^2 , 87 times that of the vehicle.

7.2 Result of experiment

For each case shown in Fig. 9, experimental results where 1 cm initial object position error was added in the direction of the x axis are shown in Fig. 10 – Fig. 13.

From Fig. 10 and Fig. 11, it is obvious that for high acceleration, both binding type (A) and nonbinding type (B) contact points can restore the desired

Fig. 12 Experimental result (contact points: (A) acceleration: low)

path of the object. However, thrust in case (A) is very large; therefore, nonbinding type (B) must be selected as the optimal contact points for minimizing fuel consumption. Therefore, the optimal contact points should be defined as those at which the norm of contact force is minimum, for transfer with high acceleration.

In the low-acceleration motion, as shown in Fig. 12, the path of the object with binding-type contact points (A) is restored to the desired path. However, in Fig. 13, it is obvious that the path of the object with nonbinding-type contact points (B) is not restored to the desired path, especially the path of θ . These two cases indicate the magnitude of DMM. Thus binding type (A) must be selected as optimal contact points for maximizing the magnitude of DMM. Therefore it is suitable that the optimal contact points be defined as those where DMM is maximum for assembly manipulation with low acceleration.

Experiments in which the initial position error is set to the y axis and initial orientation error around the z axis have also been performed. Results are the same as for the cases mentioned above.

Based on the above results, DMM is not an absolute index showing the stability of manipulation. Therefore there is little significance in comparing DMM between different desired accelerations. To obtain the index of stability of manipulation with different desired accelerations, analysis not only from

Fig. 13 Experimental result (contact points: (B) acceleration: low)

the viewpoint of mechanics but also from that of the control system is necessary. This is a problem for future studies.

8. Conclusion

In this paper, huge-object manipulation by vehicle-type robots in space has been proposed.

We have proposed two indices for the determination of optimal contact points. One is the norm of the contact force which indicates how efficiently a target object is accelerated. Another is the DMM (dynamic manipulability margin) which indicates how widely a target object is accelerated around the desired acceleration. A method utilizing spherical coordinates for the calculation of DMM, which involves less computation than previous methods, has been shown.

By considering the characteristics of transfer and assembly in space manipulation by vehicles, the optimal contact points have been defined as those where the norm of contact force is minimum and the DMM is maximum, respectively. This has been verified from experimental results using a 2DOF experimental system.

References

- (1) Cannon, R. H., Initial Experiments on the End-Point Control of a Flexible One Link Robot, *Int. J. of Robotics Research*, Vol. 3, No. 3 (1984), p. 62.
- (2) Fukuda, T., Flexibility Control of Elastic Robotic Arms, *J. of Robotics System*, Vol. 2, No. 1 (1985),

- p. 73.
- (3) Uchiyama, M., Jiang, H.Z. and Hakomori, K., Compensating Control of a Flexible Robot Arm, J. of the Robotics Society of Japan, (in Japanese), Vol. 7, No. 4 (1989), p. 20.
 - (4) Umetani, Y., Continuous Path Control of Space Manipulators Mounted on OMV, Acta Astronautica, Vol. 15, No. 12 (1987), p. 981.
 - (5) Komatsu, T., Uenohara, M., Iikura, S., Miura, H. and Shimoyama, I., The Development of an Autonomous Space Robot Operation Testbed: ASROT, J. of the Robotics Society of Japan, (in Japanese), Vol. 8, No. 6 (1990), p. 72.
 - (6) Hanafusa, H., Structural Analysis and Robust Prehension of Robotic Hand-Arm System, Proc. '85 Int. Conf. on Advanced Robotics, (1985), p. 311.
 - (7) Kerr, J., Analysis of Multifingered Hands, Int. J. of Robotics Research, Vol. 4, No. 4 (1985), p. 3.
 - (8) Nakamura, Y., Dynamics and Stability in Coordination of Multiple Robotic Mechanisms, Int. J. of Robotics Research, Vol. 8, No. 2 (1989), p. 44.
 - (9) Hanafusa, H., Stable Prehension by a Robot Hand with Elastic Fingers, Proc. 7th Int. Symposium on Industrial Robots, (1977), p. 361.
 - (10) Omata, T., Fingertip Positions of a Multifingered Hand, IEEE Int. Conf. on Robotics and Automation, (1990), p. 1562.
 - (11) Yoshikawa, T., Analysis and Control of Robot Manipulators with Redundancy. Robotics Research, Cambridge, MA: MIT Press (1984), p. 735.
 - (12) Tadokoro, S., A Measure for Evaluation of Dynamic Dexterity Based on a Stochastic Interpretation of Manipulator Motion, Proc. of 5th ICAR, (1991), p. 509.
 - (13) Zheng, X.Z., Nakashima, R. and Yoshikawa, T., Manipulability of Multiple Robotic Mechanisms in Coordinated Manipulation, Proc. of Annual Conf. of the Robotics Society of Japan, (in Japanese), (1991), p. 767.
 - (14) Kimura, H., Wang, Z. and Nakano, E., Huge Object Manipulation in Space by Vehicles, Proc. IEEE Int. Workshop on IROS'90, (1990), p. 393.
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