NON-GRAVITY UNDER-ACTUATED CONTROL METHODS OF TETHER BASED LOCOMOTION FOR ASTRONAUT SUPPORT ROBOT

TURIN, ITALY
4-6 SEPTEMBER 2012

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ABSTRACT

JAXA studies the new locomotion concept using tethers for the requests of unmanned support system for astronauts and the robot demonstration on the orbit will be planned in 2012, called Robot Experiment on JEM/ISS (REX-J). This paper introduces the details of REX-J project and explains the proposal locomotion method called the tether based locomotion. The tether based locomotion is defined as a cable driven parallel manipulator and its control method is discussed. The non-gravity under-actuated control method is focused as a control method for REX-J system and the process is explained. Then the demonstration of the proposal method using the ground test bed for REX-J operation is conducted and the results are shown.

1. Introduction

As space exploration and its utilization by humankind expand, human tasks to be conducted in space were expanded and the requests of unmanned support system for astronauts were increased. Some tasks were supported or alternated by robots, such as transporting large components or observing space facilities. Other human tasks such as assisting astronaut who is conducting Extra-Vehicular Activities (EVA) are difficult to the previous robot because such tasks requires locomotion capability to move to the workspace by itself and manipulation capability to do requested works, which is needed some new technologies for space robot. For manipulation studies, Dextre(CSA) and Robonaut 2 (NASA) were sent to International Space Station (ISS). On the other hand, JAXA is studying the locomotion capabilities for next generation space robot and the precursor robots are planned to be demonstrated on Japanese Experiment Module in 2012, called Robot Experiment on JEM/ISS (REX-J).

Next generation space robots require wide spatial locomotion capabilities which are adequate safe to work near human facilities. Oda proposed a unique mobile method using tethers and extendable robot arms, called tether based locomotion. [1] At the proposal methods, Robot is floated by tethers which are anchored handrails on the space structures using extendable robot arms. Its position and posture is changed to control tethers collaboratively. To replace the anchored point by extendable robot arms, robot can move the large area. Tether based locomotion requires two key technologies; one is the mechanisms of extendable robot arms, the other is control methods of tethers in space. Tokyo Institute of Technology (Tokyo Tech) and JAXA research the precursor model of tether based locomotion and the basis functions of tether based locomotion are demonstrated in REX-J. This paper announced the detail of REX-J project and introduced the control methods of tethers at REX-J. Proposed methods are based on the under-actuated Cable Driven Parallel methods for non-gravity circumstances. Simulation and ground test for REX-J were demonstrated and the results were shown.

2. REX-J Robot Operation Concept

2.1. Mission Concept

The REX-J mission was proposed in 2007 in response to announcement of the opportunity (AO) to collect mission ideas to be conducted on the JEM / ISS. This mission deals to be conducted on an idea of tether based locomotion. The REX-J equipments are loaded in a box-type payload whose name is Multi Mission Consolidated Equipment (MCE) attached to the JEM exposed facility (JEM-EF) as shown in Fig.1. MCE mission is also said a shared mission payload and REX-J mission is one of five missions in MCE. On July 2012, MCE will be launched by HTV/IIIB. REX-J operation will be conducted for a half year.

![](image_url) Fig.1 Multi mission Consolidated Equipment
2.2. Locomotion Capability

Supporting robots are demanded to move around the space structures such as the space station as well as astronauts. The concept of REX-J locomotion capability is to use the handrail for walking on the space facilities. The tether based locomotion use the tethers for anchoring its body to handrail. Tethers are hooked by the robot arms which consist of the extendable boom and dextrous hand. Robot can attach and de-attach the handrails on the space facilities and moves spatially in the surrounded area. Table 2 shows each method’s advantage and disadvantage and proposal method is advanced methods of “Move by tethers” [2], which is resolved the “anchoring” issues.

Table 2: Robot’s locomotion methods in space

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantage/Disadvantage</th>
</tr>
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<tbody>
<tr>
<td>Free Flying</td>
<td>Locomotion area is large and not limited. / Risk of collision, limited life by the fuel consumption is critical. (ex. AERCam)</td>
</tr>
<tr>
<td>Transferred by RMS</td>
<td>Installation is easy. / Locomotion area is limited by the reach of RMS (ex. Dextre)</td>
</tr>
<tr>
<td>Move on rails</td>
<td>Carrying capacity is large. / Locomotion area is limited by the reach of RMS and rails (ex. SSRMS)</td>
</tr>
<tr>
<td>Inchworm move on grapple fixture</td>
<td>Locomotion area is not limited by the arm length. / Locomotion area is limited by the location of the grapple fixture and carrying range is limited. (ex. SSRMS)</td>
</tr>
<tr>
<td>Move by multi arms on handrails</td>
<td>Installation is easy and locomotion area is large to use the handrail. / System becomes complex since number of degrees of freedom increase (ex. EUROBOT, Robonaut)</td>
</tr>
<tr>
<td>Move by tethers</td>
<td>Size of robot can be small while locomotion area is wide. / Robot requires astronaut’s support for anchoring tethers. (ex. Charlotte)</td>
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Fig. 2 depicts the principle of Tether based locomotion and also the sequence of locomotion is itemized by number as follows.

(1) The robot has several tethers and extendable robot arms inside body. Tethers are wound in reels. Each tether has a hook-like mechanism to attach the tether to a structure, such as a handrail, which is prepared for astronauts. Extendable robot arms can deploy and retract their boom and have a robot hand at its end.

(2) At first, the robot grasps the tether’s hook with its extendable robot arm. And then it attaches the hook to a handrail or secures itself by some other method.

(3) Retract the robot arm and repeat to attach the hooks to other points.

(4) After connecting the tethers to the facility, the robot adjusts and controls the length of each tether cooperatively to change the location of robots.

(5) The moving area depends on the number of tethers attached to the structure and the location of each tether anchoring point. Usually three tethers decide the planar moving area and four or greater ones give spatial locomotion area.

(6) If necessary, the robot changes the anchoring point using extendable robot arm and extends the locomotion area which robot can move.

Fig. 3 shows a 3D-CAD model of the tether reel mechanism of REX-J experiment model. A mechanical hook is attached at the end of the tether. This hook can be operated by a human or by a robot.

![Fig. 3 3D-CAD model of tether reel and hook](image)

2.3. Manipulation Capability

The key technology for its locomotion method is the deployable robot arm, which attaches or de-attaches the tethers to distant handrail. Such new manipulator is called “Extendable Robot Arm (ERA)” and developed for REX-J mission. ERA consists of extendable boom mechanism and human-like grasping mechanism. In REX-J, STEM robot arm system (SRAs) and JAXA-THK hand system is developed and experiment model mounts each flight model. (Fig. 4)
2.4. Robot Experiment System

The REX-J experiment system consists of two-layered body and the control system as shown in Fig.5. The upper stage is mounted the Extendable robot arm system and the lower system is mounted the tether reel system. REX-J Experiment is recorded by four cameras; three cameras on the ERAs take arm’s action and one camera on the base plate takes robot’s locomotion. In the mission, REX-J experiment system will grasp the handrail and move on the base plate.

2.5. Ground Operation System

REX-J will be operated by ground operational system as shown in Fig. 6. [3] A laptop computer named REX-J GSE-1 is used for processing command data (CMD) to the onboard system, and the other laptop computer named REX-J GSE-2 is used for processing telemetry data from the onboard system. A desktop computer named REX-J GSE-3 is used for processing camera image data from onboard cameras. Each components of REX-J onboard system is operated by command sets which consist of the simple orders for actuators, cameras. Command sets are registered into Macro functions before each operation. Each demonstration is started by the single “Macro-Go” command. Each command set is verified to check on the ground test bed.

3. Tether based locomotion

This chapter introduces the tether based locomotion which is the locomotion method for REX-J. At first, the mechanistic characteristics are introduced. Next, the kinematics and dynamics are shown and then the controllability is discussed.

3.1. Mechanistic characteristics

Tether based locomotion is a kind of multi-suspended mobile system which is the spatial mobile system floated by wires, cables or tethers and controlled by the reeling system such as ROBOCRANE [4], FALCON [5] and so on. Multi-suspended mobile system has several desirable properties like reduced mass of system, ease of reconfiguration and a potentially very large workspace. Especially, it focused on the spatial mobility and the haptic device. For example, Multi suspended camera system which can fly and shoot freely over the large workspace are now practical in the sports stadium. [6] Usually, the work space of the multi-suspended mobile system is stationary and limited by the deployment of wires because the reeling system is fixed with the circumstances. Some researcher suggests that the changeable deployment method for wires gives flexible and wide movements for mobility. For example, Hirose proposed “Hyper Tether” as a changeable deployment system which its wires are deployed by several mobile robots. [7] Tether based locomotion is also based on the changeable deployment methods, which the robot change the work space by itself to attach and re-attach the tethers with extendable robot arm. The concept is so unique that the operation procedure and control methods require a few new ideas which are specialized for space working. This paper focuses not on the deployment but on the locomotion and introduces the control method for the tether based locomotion.
3.2. Kinematics and Dynamics model

The locomotion model for Multi-suspended mobile system is proposed as a “Cable Driven Parallel Manipulator” (CDPM). CDPM is a parallel manipulator which the booms are chord members. Figure 7 shows the math model.

The motion of CDPM is depended on tethers’ lengths and their tensile forces. Usually, CDPM is difficult to be identified its position and its posture from arbitrary tethers’ length and tensile forces because tethers have no rigid. Following equations 1 - 3 are the tethers relationship which is defined by the geometrical conditions and tether’s material properties. Therefore, CDPM is difficult to define the kinematics model.

The translational and angular velocity vectors are represented as $\dot{X}$ and $\boldsymbol{\omega}$. The variations of tethers’ lengths are arrayed as $L = \{L_1, \ldots, L_n\}$. Eq. 4 is analogy of the Jacobian in the kinematics of the serial manipulator. The matrix $J$ represents the geometrical configuration between robot and tethers. In equation 5, the vector $t_i$ means the unit vector of $i$-th tether and the vector $a_i$ means the vector from the centre of mass to $i$-th end point in the robot body. Similarly, the dynamics equation is represented as follows.

$$M_i \begin{bmatrix} \dot{x} \\ \dot{\omega} \end{bmatrix} = J \begin{bmatrix} f' \\ F \end{bmatrix}$$ (6)

The matrix $M_i$ is the inertia matrix represented mass and inertia of robots. The tensile forces of each tether are arrayed as $f = \{f_1, \ldots, f_n\}$. Dynamics is also represented as linear formulation and Jacobian matrix.

CDPM is presupposed that tethers are no slack and tethers’ lengths and tensile forces are controllable. Therefore, common control methods for CDPM are based on the model based control which all tethers keep slack less.

3.3. Controllability

Not only tether based locomotion but also common CDPM have the difficulty about the controllability because the chord members have no or very few rigidity. Controllability of CDPM is defined as the number of cables which are no slack and controllable. Generally, full-constrained system is consisted of the 4or 7 cables which is the number of locomotion space added one. More cable system is defined as redundancy-actuated system and less is defined as under-actuated system.

Tether based locomotion is based on the changeable deployment methods so that the number of tethers effects the total time cost for locomotion. In additions, less actuator are desirable for space components. Therefore, the tether based locomotion is directed to the under-actuated system.

Full-constrained system and redundancy-actuated system is easy to solve the inverse kinematics or inverse dynamics to calculate the pseudo-inverse matrix which are checked the slack state to evaluate the left null spaces of Jacobian matrix. [8] On the other hands, under-actuated system is difficult to solve the inverse kinematics because controllable parameters are less than degree of freedoms. If the robot is adequate small compared with work space, locomotion model can be treated as mass point and tethers’ state can be calculated by geometrical configuration. Usually, the slack caused by the differences of mass model and rigid body which the connection point is separated are compensated by gravitation. Some researchers propose the model based control with the attitude determination to solve the
The simple control method which is realizable for the REX-J system is considered as the linear interpolation method on the joint angle space. The initial and the terminal statics states are easy to be identified and the control parameters can be calculated and mapped on the joint angle space from a CDPM math model. If the robot is small compare with deployment area, all the path made by the linear interpolation between initial and terminate position is almost nearly the statics state. However, if its size is large like REX-J experiment model, the tethers’ length determined by the interpolation may be different from statics state and will be slack or broken.

Therefore, non-gravity under-actuated control method is proposed that one tether are controlled by the current control to keep the tension and the others are controlled by the position control which the control value is determined by linear interpolation between initial and terminate statics state. Previous result showed that the statics state of planar locomotion is determined by 2 tethers because the planar model for CDPM is constrained by three tethers and one is used for the compensation of the mechanistic rigid. Proposal methods for REX-J system is shown in Fig. 9. In this paper, the current control is defined by the largest amount of rolling angles.

4. Control

4.1. Mobile control concept for REX-J system

The control concept for robotic manipulators is classified roughly in terms of control coordinate for feedback control system; joint coordinates and space coordinates. Generally, CDPM is adapted the space coordinates for the tether control system such as a reel servo system, because the model based control is required to avoid the slack of tethers. The model based control of statics model using sequential control which is based on space coordinates system was simulated at the spatial model of tether based locomotion and verified the effectiveness. However, the feedback control of space coordinate system is demanded on the complex control to tether control system and difficult to be adapted on the REX-J experiment system because its control system consists of the simple servo system and is operated by the easy macro command. Therefore, the feedback control system which based on the joint angle coordinate is considered as a non-gravity under-actuated control method for REX-J system.

4.2. Non-gravity under-actuated control method

Previous research proposed the identification method of statics state from given position. If the robot motion is slow, point to point control gives the slack less motion for tether based locomotion. (Fig. 8) However, even if the simple path such as a straight route, the variation of tether’s length and tensile forces are non-linear and the function of those are difficult to be mapped on the joint coordinate spaces.

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5. Simulation and Experiment

5.1. Simulation

Dynamics simulation for CDPM was conducted to be verified the proposal control method for REX-J. Simulation model was constructed from the drawing of REX-J experiment system and the result of tether’s characteristic experiment. Reel control system was simplified to simple PD controller.

The example of simulation is following. Fig. 10 is the image of the simulated path. Red line is the path of centre of mass and blue dot line means the deployment
area which is narrow because the experiment area is limited. This motion simulated one of the longest routes which REX-J can move. Fig. 11 and Fig.12 show the history of tether’s length and tensile forces. Tether 1 is controlled by the current control and the others are controlled by the position control. The current is limited by the tensile force. Those figures show that tensile forces are always slack less on the motion.

5.2. Experiment
Proposal method was demonstrated on the ground test bed for REX-J operation. (Fig. 13) Operation procedures are checked to operate the ground test bed which is consisted of the BBM components of robot main body and MPU from the tele-operation system shown as Fig.6. This experiment system reads out the simulated telemetry and the position and posture which are measured by the image analysis.

Fig.10 Simulated Path

Fig.11 Calculated tether’s length

5.3. Result
The example of locomotion is following. Fig. 14 is the image of experiment results drawn the movement locus of centre of markers.

Fig.13 REX-J Ground Test bed

Fig.14 Experiment Result

To evaluate the locomotion, the numerical simulation calculated by the CDPM model and measured values are compared and the results are shown in Fig.15 and Fig.16. Those figures are verified that proposal methods are effective for the REX-J system.
6. Conclusion

This paper introduced the new locomotion methods for the next generation space robots and the details of REX-J project. Then the non-gravity under-actuated control method was proposed as a control method for tether based locomotion. The model based control using statics analysis was adapted to the feedback control which is based on the joint angle coordinates for REX-J system. Proposal method was demonstrated on the ground test bed. In 2012, tether based locomotion will be demonstrated in the orbital.

7. Reference


