EVALUATION ANALYSIS OF THE S-520-25 ROCKET EXPERIMENT FOR A TETHERED SPACE ROBOT

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ABSTRACT

This paper describes evaluation analysis for the space verification experiment of a tethered space robot on the sounding rocket “S-520-25.” A tethered space robot is a new type of space systems connected to tether. The major advantage is that its attitude can be controlled under tether tension by its own link motion. The S-520-25 rocket was launched on August 31, 2010. The tether was extended and kept its tension, and attitude control of the tethered space robot was performed. The disturbed vibration of attitude was suppressed, and also the desired attitude was controlled by arm link motion of the robot. The motion analysis by mechanical dynamics software has confirmed and evaluated the space verification experimental result.

1. INTRODUCTION

Tethered space robot is a new type of space systems connected to tether, proposed in 1995 [1]. It has several advantageous characteristics. Emergency retrieval is possible by tether, and then it becomes small because of the minimum components without redundancies. There are possibilities of unexpected contact and collision for a space robot especially due to microgravity. Miniaturize of its scale and mass makes those damages minimum. It also has an advantage in energy consumption. Translation and attitude controls by tether tension are possible. Such a tethered and/or robotic system performs dynamic motion in space. However, ground dynamic experiment in 3D space is difficult, and also orbital space experiments cost high. Especially for a tethered space robot, whose mission is a new and challenging, long-term and high cost are required for development by existing process. Therefore, Kagawa University is developing a space experimental system for itself.

Many applications are expected and studied for tethered systems because of its lightness and compactness. Several space verification experiments for a tethered system have been performed, for example, Gemini-Agena program [2] and Tethered Satellite System Project [3]. On the other hand, ROTEX by DLR (Deutsches Zentrum für Luft- und Raumfahrt) [4], and Engineering Satellite #7 by JAXA (Japan Aerospace Exploration Agency) [5], etc. have been performed as a space verification experiment for a space robot.

STARS (Space Tethered Autonomous Robotic Satellite), which is a 10kg satellite developed in Kagawa University, was launched by the H-IIA rocket on 23, January, 2009. It is a mother-daughter satellite, a tethered satellite, and also a robotic satellite [6]. These three main characteristics have been evaluated and verified on orbit, though attitude control for a tethered space robot could not be performed due to shorter tether extension than expected.

On 31, August, 2010, TSR-S (Tethered Space Robot S) was launched by the sounding rocket S-520-25 from Uchinoura Space Centre by JAXA [7]. The S-520 has a capability for launching a 100 kg payload far above 300 km and provides more than 5 minutes for micro-gravity flight environments. S-520-25 performed two kinds of experiments: one is for electrical dynamic tether and the other is for a tethered space robot. The purpose of the tethered space robot experiment is evaluation and verification of the proposed attitude control approach for disturbances suppression and change of the desired attitude. Because the S-520-25 rocket flied with longitudinal rotation at 1Hz, motion of the tethered space robot became so complicated. This paper analyses the complicated motion, and then evaluates effectiveness of the attitude control approach in the space experiment, using Mechanical Dynamics Software “ADAMS.”

2. MODELING FOR A TETHERED SPACE ROBOT

2.1. Analytical model and attitude control approach

Figure 1 shows an analytical model for a tethered space robot. The robot consists of one arm and one base. One end of the arm is connected to tether, and the other end is connected to the base by a rotational joint, which has 2 degrees of freedom. The system is in equilibrium condition as shown in figure (a), when the mass centre
of the robot and the tether attachment point are located on the tether extension line. It is not in equilibrium as shown in figure (b), when it deviates from the equilibrium (a). Here defines the inertial frame \( \Sigma-XYZ \) and the robot fixed frame \( \Sigma-xyz \). The \( x \) axis is the longitudinal axis of the robot. \( r \) denotes the joint centre position vector with respect to the robot mass centre, \( l \) denotes the tether attachment point vector with respect to the joint centre, and \( n \) denotes tether tension vector, respectively. Then tether tension torque applied to the robot is described as:

\[
\tau = (r + l) \times n. \tag{1}
\]

Setting the robot fixed frame as that \( r \) is located on the \( x \) axis, and describing attitude of the robot by Euler angles \( \theta_1, \theta_2, \theta_3 \), and also attitude of the arm link by \( \phi_1, \phi_2 \) (arm link rotation is not free in the \( x \) axis), each vector can be written as:

\[
r = \begin{bmatrix} r_1 \\ 0 \\ 0 \end{bmatrix}, \quad l = \begin{bmatrix} -\cos \phi_1 \cos \phi_2 \\ \cos \phi_1 \sin \phi_2 \\ -l \sin \phi_2 \end{bmatrix}, \quad n = \begin{bmatrix} -n \cos \theta_2 \cos \theta_1 \\ n \cos \theta_1 \sin \theta_2 \\ -n \sin \theta_2 \end{bmatrix},
\]

where \( \|r\| = l \) and \( \|l\| = n \). Then, equation (1) can be rewritten as:

\[
\tau = \begin{bmatrix} 0 \\ (n r_1 - n l \cos \phi_1 \cos \phi_2) \sin \theta_1 \\ (n r_1 \cos \theta_1 - n l \cos \phi_1 \cos \phi_2 \cos \theta_2) \sin \theta_2 \\ -n l \sin \theta_1 \cos \phi_1 \sin \phi_2 + n l \cos \theta_1 \sin \theta_2 \sin \phi_1 \\ n l \cos \theta_1 \cos \theta_2 \sin \phi_1 \\ n l \cos \theta_1 \cos \theta_2 \cos \phi_1 \sin \phi_2 \end{bmatrix} + \begin{bmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{bmatrix} k_d \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix} - \begin{bmatrix} \phi_{d1} \\ \phi_{d2} \\ \phi_{d3} \end{bmatrix}. \tag{2}
\]

Assuming \( \theta_1, \theta_2, \theta_3, \phi_1, \phi_2 \ll 1 \) in equation (2), the first term is a torque by change of robot base attitude, and the second term is a torque by arm link motion. By the following attitude control equation:

\[
\begin{bmatrix} \dot{\phi}_1 \\ \dot{\phi}_2 \\ \dot{\phi}_3 \end{bmatrix} = \omega_2 \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix} - \begin{bmatrix} \phi_{d1} \\ \phi_{d2} \\ \phi_{d3} \end{bmatrix} \tag{3}
\]

the first and the second terms in equation (2) are acting as restitution and damping torques, respectively. Where, \( k_d \) denotes a control gain, \( \omega_1 \) and \( \omega_2 \) denote angular velocities in axes \( y \) and \( z \) of the base (called "control axes"), \( \phi_{d1} \) and \( \phi_{d2} \) denote the desired arm link angles determined by the desired attitude of the robot base, respectively. \( \phi_{d1} = \phi_{d2} = 0 \) when the inner product of \( r \) and \( l \) is equal to be zero under the desired attitude.

Tether tension torque can be controlled by operation of the tether attachment point with respect to the robot mass centre. That is, attitude control in the \( y \) and \( z \) axes of the robot (control axes) is possible. On the other hand, attitude in the \( x \) axis cannot be controlled. Here, the robot has "arm offset" when \( \phi_{d1} \) and/or \( \phi_{d2} \) are not equal to be zero.

2.2. Simulation model

Figure 2 shows experimental model on ADAMS (MSC Software Inc.) for the sounding rocket experiment. The experimental device consists of a tethered space robot (Robot) and a deployer (DPL). The DPL gives an initial velocity to the Robot and controls tether tension. Simulation model as shown in figure 2 is initial configuration before the experiment. Here, the DPL fixed frame and the Robot fixed frame are defined with respect to the inertial frame. The arm joint employs the differential gear mechanism as shown in figure 3. As shown in figure 2, joint A and joint B rotate \( \phi_1 \) and \( \phi_2 \) defined by Euler angles in section 2.1, respectively.

The experimental data sets are angular velocities of the Robot and the DPL, tether length, and arm link angles. The positions of the Robot and the DPL, and tether tension were not measured in the experiment. Here explains simulation approach for evaluation of attitude control effectiveness using the obtained experimental data. The DPL is rigidly connected to the DAU (Daughter: another device in the S-520-25 experiment) whose mass is much larger than that of the DPL. Therefore, DPL motion is subject to DAU motion. Then, the origin of the DPL fixed frame is fixed to the inertial frame, and DPL attitude is restricted based on the experimental data of its angular velocity. The position of the Robot mass centre is geometrically determined by the experimental data of tether length and arm link angles. Here, note that tether length should not be restricted by the experimental data, because the restriction determines tether tension, which is the
controlled value and important for the attitude control. Tether tension and arm link motion are set by control parameters. Initial condition of Robot attitude (before arm link control begins) is set based on the experimental data. Then, attitude of the Robot is obtained as a simulation result.

Simulation parameters are set as: inertial momentums of the Robot are \( I_x = 7881.76, I_y = 7387.44, I_z = 6589.94 \text{kgmm}^2 \), tether tension is \( n = 30 \text{gf} \), and attitude control gain is \( k_d = 1 \), respectively. Note that the mass does not influence on motion because position is determined by geometrically input. Also, arm offset is set as \( \phi_{yd} = -5.23 \text{deg} \) and \( \phi_{zd} = -50.23 \text{deg} \), as same as those in the space experiment.

The results in figure 4 can be summarized as follows.

- Damping of angular velocity in the longitudinal axis. Angular velocity in the longitudinal axis is damped after the attitude control begins.
- Influence of longitudinal rotation. The desired condition is changed by angular velocity in the longitudinal axis.
- Influence of arm offset on the desired condition. The desired condition is influenced by longitudinal rotation due to arm offset.

These characteristics are examined detail in the following sections by simulations with other parameter settings.
3.2. Longitudinal rotation damping
In order to examine the damping of angular velocity in the longitudinal axis after the attitude control begins, time period (i) of the x axis in figure 4 is enlarged in figure 5. Also, torque τ is plotted by calculating from ω, ωy, and ωz with inertial momenta Ix, Iy, and Iz. It is noted that integration of τ is positive in the experimental result even though it is negative occasionally, and also that τ is always positive in the simulation result.

Figure 6 shows snap shots of ADAMS animation when τ begins to decrease at (A), and when τ decreasing is small at (B), respectively. It can be said that tether tension torque is large in (A), and small in (B), respectively. Then, it can be said that tether tension torque is applied by both attitude of the Robot and arm link angles, and that ω is damped by the x axis element in the second term in equation (2).

3.3. Influence of longitudinal rotation
First, change of the desired condition by angular velocity ω in the longitudinal axis is examined detail. Figure 7 shows simulation result under condition that ω is forced in ω +15deg and ω -40deg after Robot separation from the DPL. The first line shows ω as simulation condition, and the second and the third lines show ω and ω as simulation results, respectively. It is noted that converged values of ω and ω are changed by ω. It is also noted that vibrations of ω and ω are observed clearly when ω is large.

Second, it is examined detail that angular velocities ωy and ωz in the control axes decrease after the attitude control begins. ωy and ωz with respect to ω in equilibrium under condition of φyd = -5.23deg and φzd = -50.23deg are examined by simulation. The result values are plotted in figure 8. Here, the vector product of ω, ωy, ωz and tether tension n becomes equal to be zero. It can be said that angular velocities in the control axes is determined by angular velocity in the longitudinal axis at the desired condition.
Figure 9 shows the experimental result in figure 4 with the results in figure 8. The cross shows $\omega_x$ and black circle shows $\omega_y$ and $\omega_z$ at the desired condition, respectively. It is noted that vibration centres of $\omega_y$ and $\omega_z$ are qualitatively subject to the desired condition.

3.4. Influence of arm offset

It is examined in section 3.3 that the desired condition is influenced by longitudinal rotation. It is also noted from equation (2) that the influence appears when the Robot has arm offset at the desired condition. Here examines motion in case that the Robot does not have arm offset. Figure 10 shows simulation result when the Robot does not have arm offset ($\phi_0 = \phi_d = 0$) with the result in figure 4. Here, $\phi_d = \alpha$ expresses $\phi_d = -5.23$deg and $\phi_d = -50.23$deg, and $\phi_d = 0$ expresses $\phi_d = \phi_d = 0$, respectively. It is noted that the centre values of angular velocities in the control axes are qualitatively zero, however they include vibrations. Then, it is considered that angular velocity vibrations in the control axes are caused by longitudinal rotation.

In order to confirm that vibrations of $\omega_y$ and $\omega_z$ are due to $\omega_x$, simulation result in case of $\omega_x = 0$ is shown in figure 11. It is noted that $\omega_y$ and $\omega_z$ are almost converged to be zero in both cases with and without arm offset. Then, it can be said that longitudinal rotation...
causes angular velocity vibrations in the control axes. In other words, longitudinal rotation is considered to be disturbances against to the desired condition.

- Influence of arm offset on the desired condition. Angular velocity at the desired condition becomes to be qualitatively zero in case without arm offset.

Longitudinal rotation causes angular velocity vibrations in the control axes, it is considered to be disturbances against to the desired condition.

5. REFERENCES