On-Orbit Experiment of Vision-Based Motion Estimation and Tracking of Tumbling Object in Space

By Ryu FUNASE,1) Shinichi NAKASUKA,1) Nobutada SAKO,1) Takeshi FUJIWARA,2) Yuichi TSUDA,3) Shinichi UKAWA,4) Shinichi KIMURA,5) Hidekazu HASHIMOTO,6) Keisuke YOSHIHARA6) and Toru YAMAMOTO6)

1)Department of Aeronautics and Astronautics, The University of Tokyo, Tokyo, Japan
2)Aviation Program Group, Japan Aerospace Exploration Agency, Chofu, Japan
3)Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Japan
4)Mitsubishi Electric Corporation, Kamakura, Japan
5)Space-info Network Group, New Generation Wireless Center, National Institute of Information and Communications Technology, Yokosuka, Japan
6)Institute of Aerospace Technology, Japan Aerospace Exploration Agency, Tsukuba, Japan

(Received April 10th, 2006)

Capture of tumbling objects in space will be one of the important on-orbit service technologies in the future. It requires a series of technologies such as camera-image tracking of the target, target attitude motion estimation, and attitude control of the chaser to approach and grasp the target. Based on theoretical and simulation-based research, the University of Tokyo successfully performed an on-orbit experiment of some of these technologies on a Japan Aerospace Exploration Agency’s (JAXA, formerly NASDA) microsatellite named “µ-LABSAT.” In this paper, the objectives and procedures of these experiments, the control and estimation algorithms, and the results are described.

Key Words: Spacecraft Control, On-orbit Service Missions, Attitude Control, Image Processing, Kalman Filter

Nomenclature

\( \omega_t \): angular velocity of the target expressed in the target’s body coordinate frame
\( I_i^t \): inertia tensor of the target
\( q_i^b \): quaternion of the target’s body coordinate frame relative to the reference coordinate frame
\( f \): focal length of the camera
\( I_j \): principal moments of inertia \((j = 1, 2, 3)\)
\( I_j^b \): moments of inertia ratios \((= I_j/I_3, j = 1, 2)\)
\( \Delta t \): observation interval of the camera

Subscripts

r: reference (inertial) coordinate frame, which is supposed to coincide with the satellite’s body coordinate frame
t: target, or target’s body coordinate frame
i: i-th characteristic point on the target
C: camera coordinate frame, whose z-axis is perpendicular to the camera screen

1. Introduction

Capturing tumbling objects in space will be one of the important on-orbit service missions in the future. Tumbling objects may be satellites that have lost attitude control function, debris or manned vehicles, in each case of which it would be desirable to capture the object to repair or insert into the atmosphere (Fig. 1). Sometimes, such operation should be conducted very quickly and safely, especially when important data, expensive systems or human crew are aboard the tumbling object.

In order to safely capture the tumbling object, the first step will be to determine the relative location of the object and perform rendezvous with it, and the next step will be to estimate the target rotational motion after reaching the vicinity of the object. For these steps, images obtained by a camera-type device will provide effective information. As to the motion estimation using visual information, conventional methods assume that the shape and mass distribution of the object are known, or the object is marked with some easily distinguishable sign. Therefore, they cannot deal with the object whose geometric or inertial parameters are unknown, such as in the cases of space debris, broken satellites, etc. On the other hand, using a sequence of the angular velocity extracted from the motion image, inertial parameters of an object can be estimated.1) However, it takes a long computational time because this requires many iterative computations such as nonlinear least square method. In our previous research,2) we showed that a chaser satellite can estimate the target rotational velocity and moments of inertia ratios in real time using the images of the target obtained by a single camera on the chaser.

The third step will be to actually capture the object without much impact, which requires delicate control of the manipulator and attitude of the chaser. Though there are many studies on autonomous capturing of a tumbling object in space, almost all of them focus on adjusting only the motion of the grasping equipment, such as a manipulator, to the target’s motion.3) Therefore, because of the
mechanical limits of the equipment, only targets with slow or simple motion can be dealt with. Actual debris or uncontrollable satellites may tumble faster and more complicately; thus, a more applicable capturing method should be developed for practical use. In our previous research, Arikawa, et al. 4) showed that a certain control algorithm based on visual feedback can make the chaser’s manipulator arm reach a certain point of the target even if the point is moving. Additionally, Tsuda, et al. 5) proposed a novel control algorithm which can very quickly and efficiently synchronize the chaser’s motion with that of the target so that the relative velocity between the chaser manipulator arm and the point on the target to be grasped can be cancelled.

“Line Of Sight (LOS) control,” which means the chaser’s attitude control to keep the line of sight of its camera or other sensors towards a certain direction, is another important technology for rendezvous/docking. A new control algorithm for LOS control has been developed. 8) Named the Switching time Search Controller (SWSC), it mimics an optimal bang-bang control profile within on-line limited computational resources. The control algorithm is specially designed to deal with the unique feature of a microsatellite named “μ-LABSAT” (Fig. 2) that only two wheels (one is a bias momentum wheel and the other is a reaction wheel) can be used to control the bias-momentum three-axis stabilized satellite. μ-LABSAT is Japan Aerospace Exploration Agency’s (JAXA, formerly NASDA) first in-house satellite, aiming for the in-house development of microsatellite technologies as well as hands-on training of young engineers in JAXA. The flight model was launched successfully using a H-IIA launch vehicle on December 14, 2002.

Based on our theoretical and simulation-based research, an on-orbit motion estimation and visual tracking experiment was performed on May 14, 2003, which aimed to demonstrate part of these technologies using μ-LABSAT. In the experiment, a small object was released from the bottom of the satellite and its images were captured continually by a camera onboard the satellite. The target attitude motion parameters were estimated using these images and the LOS control algorithm controlled the target image position on the camera screen to a pre-defined target point.

The remainder of this paper is organized as follows. In Section 2, the details of the on-orbit experiment are described first, and then the technologies used for the experiment are described; such as the motion estimation algorithm based on Kalman filter and LOS tracking attitude control algorithm. In Section 3, the results of the on-orbit motion estimation and visual tracking experiment are presented and some “lessons learned” are discussed. Finally, conclusions are given in Section 4.

2. Technologies Used for On-Orbit Experiments on μ-LABSAT

2.1. Experimental setup and scenario

Using a CMOS camera and multi-chip module (MCM)-based onboard computer (MOBC) developed by the National Institute of Information and Communications Technology (NICT, formerly the Communications Research Laboratory), the motion estimation and visual tracking experiment was performed in the following way (Fig. 3).

1) A target, 10-cm diameter small object with some visual markers on the surface (Fig. 4), was released from the bottom of μ-LABSAT.
2) When it came into the field-of-view of the camera, the motion estimation experiment was initiated. The target images were obtained in roughly two-second intervals.
3) The motion of the visual markers on the surface was tracked using a specific image-processing algorithm, and applying the position information of these markers on the
camera screen, the target attitude and attitude rate as well as moments of inertia ratios were estimated using a Kalman filter. The details of the algorithm are given in Section 2.3.

4) About 180 seconds later, when the target images became too small to be used for attitude motion estimation, the visual tracking experiment was initiated, in which the chaser (µ-LABSAT) controlled its orientation so that the target image came to a specific point on the camera screen. The control algorithm is described in Secs. 2.4 and 2.5.

2.2. Image processing system in the experiment

For detecting the target position in images, the color information of the target (yellow and black) was utilized to discriminate the area of the target image from the black space background and the blue-white image of the Earth. Especially, the image of the Earth, whose color distribution cannot be predicted because of the ambiguity of how the clouds cover the Earth, had to be clearly discriminated from the target image. Moreover, it is difficult to accurately predict the intensity of the sunlight reflected off the target’s surface. For these reasons, how to tune the threshold values (for brightness and two color difference signals Y/Cr/Cb) to discriminate the target from the background is rather difficult, and it is risky to use the predefined thresholds.

In order to deal with this ambiguity, it was made possible to uplink the thresholds for image processing during the actual experiment, seeing the images of the target and Earth in near real time. A special information system, called ‘Quick Look (QL) system,’ was developed for this purpose. It can process downlinked data and display the images in quasi-real time fashion to support quick decision making.

2.3. Target motion estimation experiment using tracking of multiple characteristic points

Target motion as well as mass property (moments of inertia ratios) can be estimated by tracking the positions of several characteristic points on the camera screen. Based on Fujiwara, et al., a Kalman filter was designed to estimate these motion-related parameters as state variables from the observation data of the trajectories of the characteristic points. In the on-orbit motion estimation experiment, con-
considering the limited computational resources onboard, only the positions of the characteristic points were calculated by MOBC, and Kalman filter processing was conducted on-ground using the observation data downlinked via communication link from the satellite.

In designing the Kalman filter, it was assumed that the orbital motion and rotational motion of the satellite on which the camera was mounted are negligible and can be regarded as perturbations, and that the reference (inertial) coordinate frame coincides with the satellite (μ-LABSAT) body coordinate frame.

The state variables to be estimated in the Kalman filter include: (1) relative position \( r_{rel} \) and velocity \( v_{rel} \) of the target’s center of gravity (C.G.) expressed in the reference coordinate frame, (2) attitude quaternion of the target \( q_i \), (3) angular velocity of the target \( \omega_i \), (4) moments of inertia ratios \( I_{1i} \), \( I_{2i} \) of the target (only these two parameters are used since we assume that the target’s body coordinate frame is fixed along its principal axis of inertia), and (5) positions of the \( i \)-th feature points \( r_i^C \) expressed in the target’s body coordinate frame. The number of the state variables is \( 15 + 3n \), where “\( n \)” indicates the number of observed characteristic points. The state equations are expressed as follows,

\[
q_i^t = \frac{1}{2} Q_i^t \omega_i^t \quad (1)
\]

\[
\dot{\omega}_i^t = -I_i^{-1}(\omega_i^t \times I_i^t \omega_i^t) \quad (2)
\]

\[
\dot{r}_{rel}^t = v_{rel}^t \quad (3)
\]

where, \( Q_i^t \) is the coefficient matrix derived from the components of \( q_i^t \) such as;

\[
Q_i^t = \begin{bmatrix}
-q_1 & -q_2 & -q_3 \\
q_0 & -q_3 & q_2 \\
q_3 & q_0 & -q_1 \\
-q_2 & q_1 & q_0
\end{bmatrix} .
\]

The observations include the two-dimensional positions on the camera screen for the characteristic points on the target, which are tracked in the image-processing system. The position \( u_i \) and its displacement between observations \( v_i \) of \( i \)-th feature point on the two-dimensional camera screen are obtained from perspective conversions as follows,

\[
u_i = \frac{f}{z_i^C} \begin{bmatrix} x_i^C \\ y_i^C \end{bmatrix} \quad (5)
\]

\[
v_i = \frac{f \Delta t}{z_i^C} \begin{bmatrix} x_i^C \\ y_i^C \end{bmatrix} - \frac{z_i^C}{z_i^C} \begin{bmatrix} x_i^C \\ y_i^C \end{bmatrix} \quad (6)
\]

where, \( x_i^C, y_i^C, z_i^C \) and \( x_i^C, y_i^C, z_i^C \) are components of vectors \( r_i^C \) and \( r_i^C \), and the upper-right subscript \( C \) means the value is expressed in the camera coordinate frame.

Vectors \( r_i^C \) and \( r_i^C \) are expressed as follows,

\[
r_i^C = C_i^f(C_i^r + r_{rel}^t) - r_i^C \quad (7)
\]

\[
r_i^C = C_i^f(C_i^r \times r_i^t + v^t_{rel}) \quad (8)
\]

where, \( C_i^f \) and \( C_i^r \) are the direction cosine matrices from the target’s body coordinate frame to the reference coordinate frame and from the reference coordinate frame to the camera coordinate frame, respectively. These matrices can be expressed using the components of \( q_i \) and \( \omega_i^t \); the former is part of the state variables, and the latter is calculated with the information of how the camera is attached to the satellite. Consequently, observations \( u_i \) and \( v_i \) can be expressed with the state variables, and thus the Kalman filter can be formulated.

For the Kalman filter processing, we should consider the special condition that the characteristic points may appear and disappear irregularly. At those occasions, the states and covariance matrix are to be appropriately modified to follow the change in the number of observed points. The algorithm was implemented with this function, and was verified by computer simulations and a ground experiment using a three-axis motion simulator such as shown in Fig. 8. The convergence of the filter was assured, and even with only one camera, motion parameters were estimated.

2.4 Visual tracking experiment

In the visual tracking experiment, the onboard control system should autonomously move the target image position on the camera screen to a specific “target point.” The special feature of μ-LABSAT (Fig. 9), that the attitude should be controlled using only two wheels (\( x \)-axis reaction wheel “WHL-R” and \( z \)-axis momentum wheel “WHL-M”), requires not-straightforward type control algorithms. For this objective, a novel control algorithm named “SWSC” was derived based on optimal control theory. In this experiment, the observed state variables to be input to the control algorithm were the position (\( x, y \)) of the target image on the camera screen, body angular rates provided by the fiber optic gyros (FOG), and the angular momentums of the two wheels (Fig. 9). The control was made using only these two wheels, and magnetic torquers were not utilized in this experiment.

2.5 Switching time search controller (SWSC)

The SWSC algorithm mimics an optimal control profile in real-time fashion. The optimal profile which minimizes
the time to reach a certain target position on the camera screen can be obtained using optimal control algorithms such as sequential conjugate gradient and restoration algorithms (SCGRA). Such off-line type algorithms are, however, usually very computationally intensive, and so cannot be employed on onboard computers in real-time fashion. The time profile of the control input has a certain common feature, so if it can be mimicked in some way, the optimality of the control is approximately realized. By considering only time optimal attitude maneuvers for a bias-momentum two-wheel satellite, SWSC can generate a quasi-optimal control profile within onboard limited computational resources.

The upper-left figure of Fig. 10 shows a typical example of an optimal control input profile obtained by SCGRA, and the lower figure shows one example of target image motion on the camera screen. The control profile shows a certain bang-bang type switching, and this feature is always observed in the obtained solutions. SWSC mimics this profile in the following way.

(a) Given the initial \( p_{z0} \) (\( x \)-axis momentum is initially 0), the final angular momentums of the \( x \)- and \( z \)-axis \( (p_x, p_z) \) wheels can be predicted using the angular difference \( \theta \) between the initial body \( z \)-axis and the final \( z \)-axis as follows:

\[
\begin{align*}
  p_x &= p_{z0} \sin \theta \\
  p_z &= p_{z0} \cos \theta
\end{align*}
\]

(b) The time required to reach the final angular momentum of the wheels can be obtained by the difference between the initial and final momentums of the \( x \)-axis wheel divided by the maximum torque of the \( x \)-axis wheel. This time is called \( T_f \) hereafter.

(c) The \( x \)-axis wheel keeps the maximum or minimum torque during 0 to \( T_f \). Whether it keeps maximum torque or minimum torque is to be decided using the required momentum change direction for the \( x \)-axis wheel.

(d) The \( z \)-axis wheel changes its sign twice as in the upper-right figure in Fig. 10. There are two degrees of freedom (DOF); that is, two switching times (\( t_1 \) and \( t_2 \) in Fig. 10) that should be specified. One of these DOFs is utilized to make the total integrated torque, which is equal to the momentum change of the \( z \)-axis wheel, to be the required momentum change of the \( z \)-axis wheel calculated in (a). The other DOF can be utilized to make the final target position as near to the target point as possible. Its best value is searched for in a one dimensional search using an attitude motion simulator before the actual control in the onboard computer.

After \( T_f \), the residual target position error and satellite angular velocity are to be diminished by a simple feedback.
controller which feedbacks the difference between the current and desired values of the observed state variables.

3. On-Orbit Experiment Results

3.1. Overview and obtained images

The experiment was performed on May 14, 2003, from 10:42 am (JST), when the Okinawa ground station established the RF link to μ-LABSAT. At 10:52:30, the target appeared on the camera image, and soon the onboard system could recognize its position successfully. The onboard system then tracked the target position for more than 7 minutes without any mistake, resulting in the acquisition of 93 images including 49 target zoomed-in images. These images were continually sent to the ground station and displayed on the Quick Look system, which informed us of the normal operations of the experimental system.

Figure 11 shows some of the obtained images. The upper four figures show the examples of low-resolution images during the initial phase when target recognition was still underway. During this phase, the threshold value was to be re-tuned, if needed, through observation with the Quick Look system. In the actual experiment, however, this re-tuning was not needed. When target recognition was successfully made, the target images were extracted from the whole images and high-resolution zoomed-in images were downlinked (the lower six figures). The onboard system analyzed them to extract the positions of characteristic points, which were downlinked together with the images. The Kalman filtering operation was performed on-ground using these downlinked data to obtain the target motion parameters.

3.2. Results of motion estimation experiment

Figures 12, 13, 14 and 15 show the estimation results for the moments of inertia ratios of the target, the velocity of the target C.G., the target attitude in quaternion, and the angular velocity of the target, respectively. It was indicated that the Kalman filter almost converged in 50 seconds, and the velocity estimation showed that the target separation speed and direction (7.4 mm/s, 8 deg from z-axis) were within the designed value (0.7 cm/s to 1.0 cm/s, less than 20 deg from z-axis). The estimated quaternion and angular velocity showed an Euler rotation, from which the moments of inertia ratios were estimated ($I_1 = 1.19$, $I_2 = 1.13$) within 10% error of the true value (1.22 and 1.11, respectively).

3.3. Results of visual tracking experiment

Figures 16 and 17 show the generated torque command and trajectory of the target on the camera screen during the visual tracking experiment, respectively. The $x$-torque command kept the maximum value, while the $z$-torque command changed its sign twice as designed, where $t_1$ of SWSC (in Fig. 10) was zero. At 44 seconds ($= T_f$), SWSC completed the control, when the target image position reached (321,214), which is near to the target position (317,228).

After $T_f$, the feedback controller tried to diminish the error of SWSC control, but failed and the angular velocity showed divergent behavior (Fig. 18). The safety assurance system on MOBC successfully switched the control mode from the feedback control to the pre-defined restoration mode, and the control experiment was safely stopped.

The post-experiment analysis indicated that the system information delay in the control loop was more than expected, which probably resulted in the instability of the feedback loop. In this experiment, the delay is caused both by the sampling interval of the attitude-related information such as angular velocity of the satellite, and by the interval of the communication between OBC and MOBC. These intervals are constant but the total information delay is not constant as a function of time. This is because the sampling interval and the communication interval are not identical, and the relative timing of sampling and communication always changes. Thus, the estimation of actual information delay at any timing in the experiment is difficult. In Fig. 19, the tracking control was simulated where the theoretical maximum information delay was assumed, and the divergent profile roughly coincided with that of Fig. 18.
Consequently, it can be said that the divergent behavior was due to the information delay.

This “lessons learned” indicates the importance of precisely and thoroughly analyzing the effect of information delay caused by the timing of sensor sampling, communication interval between CPUs and other delay factors with a hardware in the loop (HIL) simulator.

4. Conclusions

Real-time target attitude motion estimation and autonomous LOS control will be indispensable technologies for future on-orbit service missions such as rendezvous/docking with, or capturing of target satellites to be served.

For motion estimation using visual information, a Kalman filter-based online estimation method was proposed, which can estimate the motion parameters and mass properties of the target simultaneously. For LOS tracking control, a com-
putationally reasonable method to generate a quasi-optimal control profile was proposed.

After these methods were verified using computer simulations and/or ground tests, an on-orbit motion estimation and visual tracking experiment was performed using μ-LABSAT. In the experiment, the motion of the target released from the satellite was correctly estimated by the Kalman filter, and the LOS tracking control algorithm could change the attitude of the satellite so that the target image moved to the designated position on the camera screen. It can be said that the experiment was quite successful, with results showing that the proposed methods are effective for future on-orbit service missions.

Fig. 19. Simulated control result for angular velocity, where it is assumed there exists a 2.4 second delay in the information of angular velocity and angular momentum given to the feedback controller. The divergent profile of feedback control roughly coincides with the actual profile in Fig. 18.

References