INNOVATIVE TEST-BEDS FOR VALIDATION OF MOTION RECOGNITION SYSTEMS INTENDED FOR ORBITAL CAPTURE MANOEUVRES

Tomasz Rybus (1), Karol Seweryn (1), Janusz Grzybowski (1), Janusz Nicolau-Kukliński (1), Rafał Przybyła (1), Tomasz Szewczyk (1), Konrad Bojar (2), Mateusz Maciaś (2), Mateusz Wolski (2)

(1) Space Research Centre of the Polish Academy of Sciences (CBK PAN), Bartycka 18a str., 00-716 Warsaw, Poland, trybus@cbk.waw.pl

(2) Industrial Research Institute for Automation & Measurements (PIAP), Jerozolimskie Av. 202, 02-486 Warsaw, Poland

ABSTRACT

Information on target object motion is required to perform capture manoeuvre during Active Debris Removal or On-Orbit Servicing mission. A visual camera mounted on the servicing spacecraft can be used to estimate motion parameters of the target object if such object is uncooperative and uncontrolled (could be tumbling). In this paper we present two test-beds developed for validation of motion recognition systems. On the first, "virtual" test-bed, motion recognition algorithm is tested on an artificially visualized motion of the target object (simulation of view from camera during on-orbit rendezvous). On the second test-bed, the motion recognition system is observing a scaled mock-up of the target object that is rotated by a dedicated 3 DOF manipulator to simulate its rotational motion.

1. INTRODUCTION

Autonomous unmanned servicing spacecraft performing Active Debris Removal (ADR) or On-Orbit Servicing (OOS) missions require information on target object motion in order to execute close proximity manoeuvres and capture [1]. If the target object is uncooperative, its motion parameters, i.e., relative position, orientation, linear and angular velocity, must be estimated based on measurements performed by sensors on-board the servicing spacecraft. Uncontrolled target object may rotate around a certain axis or might be tumbling, what makes estimation of motion parameters more difficult. Target inertia parameters must either be known or estimated to predict its motion. Accurate evaluation of object motion is especially important in case of capture performed with the use of a manipulator, as in such a case high precision is required for grasping of the target.

Various techniques are considered for estimation of target motion. One possible approach is to use visual sensors. In such an approach, a camera (operating in the visible spectrum) provides view of the target object. Images are analysed by a specialized algorithm and target motion can be estimated. Numerous algorithms were proposed for this purpose (e.g., iterative recursive least-square pose refinement [2]). Review of significant papers describing research connected with systems for estimation of target motion can be found in [3].

All devices designed to be used in space must be thoroughly tested in relevant conditions before flight. Systems for visual motion recognition are no exception. Special test-beds are required to test both algorithms at early stages of development and complete systems that include hardware components. Artificially generated videos are usually used for initial testing of algorithms (e.g., [2], [4]). Preparation of such videos is low-cost and offers a possibility to analyse algorithm performance in various conditions (e.g., different lighting). Another possibility is to capture movement of a target object mock-up. Entire systems for estimation of target motion parameters, including hardware components, can be tested in test-beds that allow rotations of such mock-ups. In the most common approach, industrial manipulators are used to rotate the mock-up of the target object and reproduce its free motion (e.g., [5], [6]).

In this paper we present two test-beds developed at Space Research Centre of the Polish Academy of Sciences (CBK PAN) for validation of motion recognition systems. On the first test-bed (called the "virtual" test-bed), the algorithm for motion recognition is tested on an artificially visualized motion of the target object (i.e., a simulation of view from the motion recognition system camera during on-orbit rendezvous). On the second test-bed, a complete motion recognition system is observing a scaled mock-up of the target object that is rotated by a dedicated manipulator to simulate rotational motion of a free-floating body. Both test-beds were developed in the frame of ESA PECS project no. 4000107934/13/NL/KML "Robust, unsupervised visual motion recognition of non-cooperative satellite for on-orbit capture" (led by Industrial Research Institute for Automation and Measurements with CBK PAN as subcontractor). The goal of this project is to develop a new visual motion recognition system and validate it using the two aforementioned test-beds. The proposed motion recognition system uses an approach in which the input image is matched with 2D images depicting various poses of the target. Then transformations from model images to the acquired image are obtained by means of a method assuring global optimality.

This paper is organized as follows. In section 2, driving requirements for both test-beds are presented and details of target object motion simulation are provided. Section 3 is focused on the "virtual" test-bed, while the second test-bed, based on a dedicated manipulator, is described in section 4. The paper concludes with section 5, where a short summary is presented.

2. DESIGN DRIVERS

Although both test-beds described in this paper are versatile, they were designed for validation of a specific motion recognition system developed in the frame of ESA PECS project "Robust, unsupervised visual motion recognition of non-cooperative satellite for on-orbit capture", thus their design was influenced by the requirements for this motion recognition system. It is, therefore, justified to briefly present these requirements herein.

The visual motion recognition system developed in the aforementioned project is intended for use during the rendezvous manoeuvre on low Earth orbit (LEO). Main purpose of the system is to determine motion parameters of a target object basing on: (i) visual observations of known structure of the target satellite performed by a single camera mounted on a rendezvousing spacecraft, (ii) rangefinder measurements of relative distance between the satellites, and (iii) knowledge of the approximate inertia parameters of the object. The proposed motion recognition system is intended for the final phase of the orbital rendezvous, when relative distance between the target object and spacecraft equipped with the system is not larger than 20 m. The target object is assumed to be uncooperative and without any markers that can assist pose estimation. Moreover, it is assumed to be uncontrolled and could be tumbling with Euclidean norm of the angular velocity vector of up to 10 deg/s. The proposed motion recognition system could be used to determine motion parameters of various objects. However, for the purpose of the motion recognition system validation, it was assumed that the target object resembles a LEO communication satellite.

From these requirements for the motion recognition system, the following requirements for the test-bed developed for validation of this system can be derived:
- Test-bed shall allow simulation of view of the target object mock-up in range from 3 m to 20 m.
- Test-bed shall allow motion of the target object mock-up with maximal angular velocity of at least 10 deg/s (no motion with linear velocity is required).
- Time of experiment shall allow more than one full rotation of target object mock-up.
- Lighting conditions of LEO shall be simulated.

As it is assumed that the target object is uncontrolled, its rotational motion is described by Euler's rotation equation:

$$\mathbf{I}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times (\mathbf{I}\boldsymbol{\omega}) = 0 \qquad (1)$$

In short time-scale any external forces, resulting, e.g., from gravitational gradient, can be omitted. In the general case of rotational motion considered herein, there is no single fixed axis of rotation. Instead, Eq. 1 can result in a tumbling motion of the target object. Such case is much more challenging for the motion recognition system, as orientation of the target object (described e.g., by Euler angles) can change rapidly. As an example, we present results of simulation of tumbling motion of a target object. In Fig. 1 orientation of the target object is presented, while in Fig. 2 its angular velocity (in body reference frame) is shown.

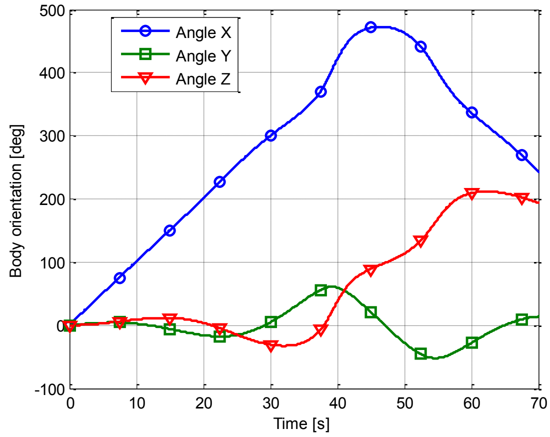

Figure 1. Orientation of the target object described by Euler angles (in ZYX convention).

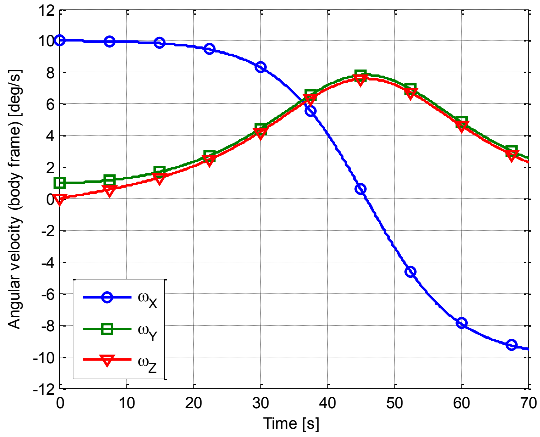

Figure 2. Angular velocity (in body reference frame) of the target object.

3. VIRTUAL TEST-BED

The "virtual" test-bed was created to allow preliminary tests of the motion recognition algorithms on an early stage of the project (before implementation of the algorithm on a breadboard). A Matlab script is used to simulate motion of the target object and then CATIA

V5 R18 is used to create artificial video images that simulate view from the motion recognition system camera.

A detailed model of the target object is used in the "virtual" test-bed. In the project described herein, a target object resembling LEO communication satellite was chosen for the purpose of motion recognition system validation. Thus, a model of such satellite was created in Inventor 2010 CAD Software and then transferred to CATIA. Material properties of particular surfaces were selected to closely resemble (in various lighting conditions) the materials used on satellites. Special attention was given to modelling of the multi-layer insulation (MLI) cover of the satellite, as the light reflections from the MLI cover could significantly hinder the performance of the motion recognition system. The model of the satellite is presented in Fig. 3. This model is connected to a mechanism created in CATIA environment. This mechanism consists of three rotational and three translation joints, thus it gives the satellite all 6 DOF.

To obtain realistic video images, the lighting conditions of LEO were also carefully modelled in CATIA, including direct sunlight and scattered light from Earth surface. Final rendering of the target object is presented in Fig. 4 (in black and white, as a black and white camera will be used in the proposed motion recognition system). Animations can be created with various background: from simple uniform black background, through background with stars, to more complex backgrounds containing views of Earth surface or Earth horizon. The case of the orbital rendezvous with Earth surface visible behind the target object could be particularly challenging for the motion recognition system. In such a case, cloud formations and land structures at all possible characteristic scales could be seen, as well as uniform surfaces like a sea. Moreover, as a single pixel is smaller than 1km, a man-made infrastructure is also visible. The vast variety of visible structures, both natural or man-made, can produce unpredictable patterns that can contain arbitrary shapes (e.g., highways can produce straight lines in the image). These shapes can resemble parts of the target and pose problems for the motion recognition algorithm. Rendering of the target object with Earth surface as a background is presented in Fig. 5.

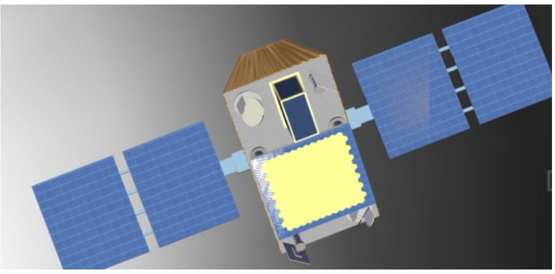

Figure 3. Model of the target object.

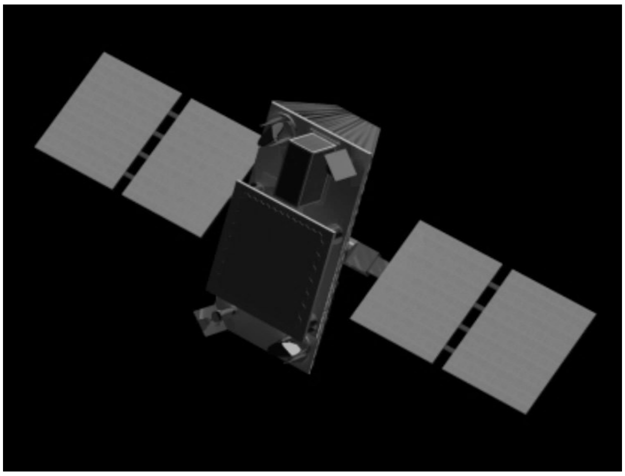

Figure 4. CATIA rendering of the target object - simulation of view from the motion recognition system camera during on-orbit rendezvous.

Figure 5. CATIA rendering of the target object with Earth surface as a background.

In the "virtual" test-bed, the motion of the target object is simulated in CATIA using input files generated by the Matlab script that simulates the motion of the object. Afterwards, rendering is performed to produce an output video file in a format resembling images captured by camera of the motion recognition system. Noise effects can be added to the video during post processing.

The "virtual" test-bed can be very useful, as it can allow rapid assessment of algorithm performance in various environmental conditions and with different motion parameters of the target object. Frames from the "virtual" test-bed video presenting tumbling motion of the target object are presented in Fig. 6. This is the motion that was earlier presented in Fig. 1.

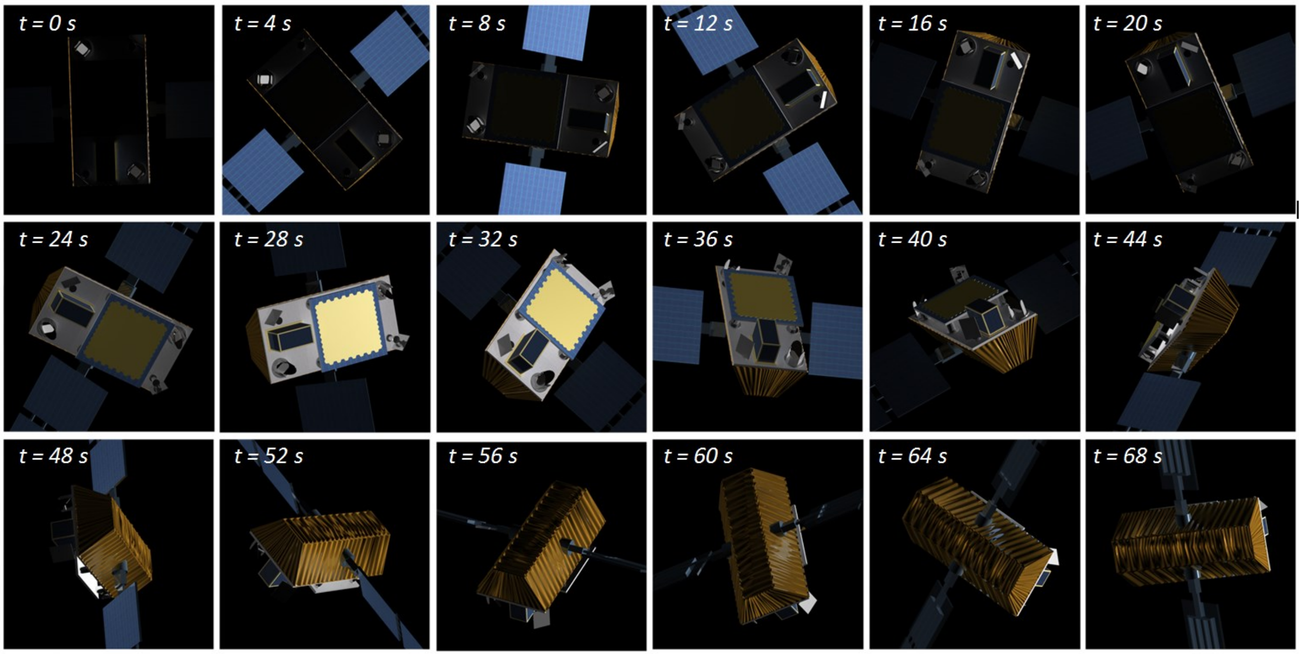

Figure 6. Frames from "virtual" test-bed video (created in CATIA) presenting tumbling motion of target object.

4. TEST-BED BASED ON DEDICATED 3 DOF MANIPULATOR

The second test-bed is intended for performance verification of the entire motion recognition system (including its hardware). In a common approach, during tests of motion recognition systems for orbital applications, industrial manipulators are used for rotating the target object (e.g., [5], [6]).

When such manipulators are used, rotational motion of the mock-up is limited, and in some configurations large parts of the mock-up can be obscured by the manipulator links. Analysis of the requirements for motion recognition system developed in frame of ESA PECS project "Robust, unsupervised visual motion recognition of non-cooperative satellite for on-orbit capture" showed that the use of industrial manipulators would not allow us to verify whether all crucial requirements are fulfilled. Thus, a new test-bed was required that would allow simulation of tumbling motion of the target object for a long period of time and with high rotational velocity (up to 10 deg/s). Such test-bed was designed and manufactured at CBK PAN. Conceptual illustration of this test-bed is presented in Fig. 7, while its photo – in Fig. 8.

The main part of the test-bed is a mock-up motion system, which is a dedicated 3 DOF manipulator used to rotate a mock-up of the target object (linear motion of the mock-up target object cannot be performed on this test-bed, but it is not required for validation of the motion recognition system). Due to the limited space in the laboratory, scale of the mock-up had to be reduced.

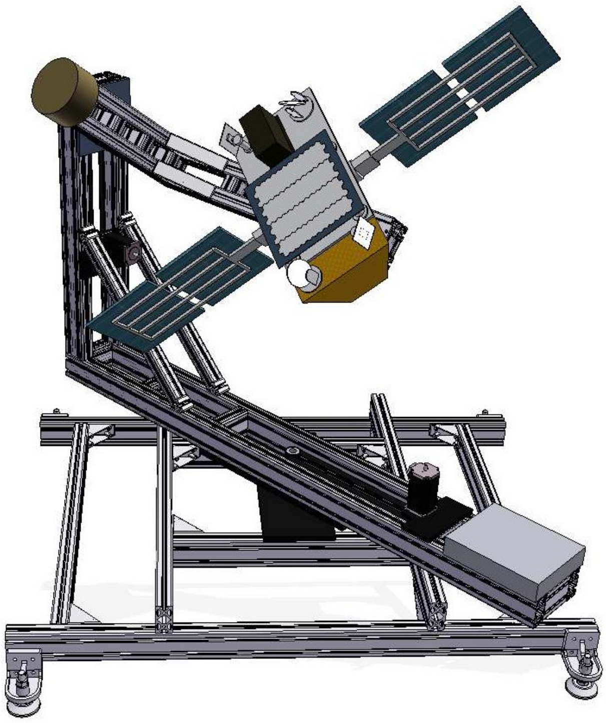

Figure 7. Conceptual illustration of test-bed based on a dedicated 3 DOF manipulator.

Maximal length of a rotated object must not be higher than 1.25 m, thus in the frame of the aforementioned ESA PECS project the mock-up satellite resembling a LEO communication satellite was built in the scale 1:6. The reduced scale is not a problem, as observations with the motion recognition system on the test-bed can be

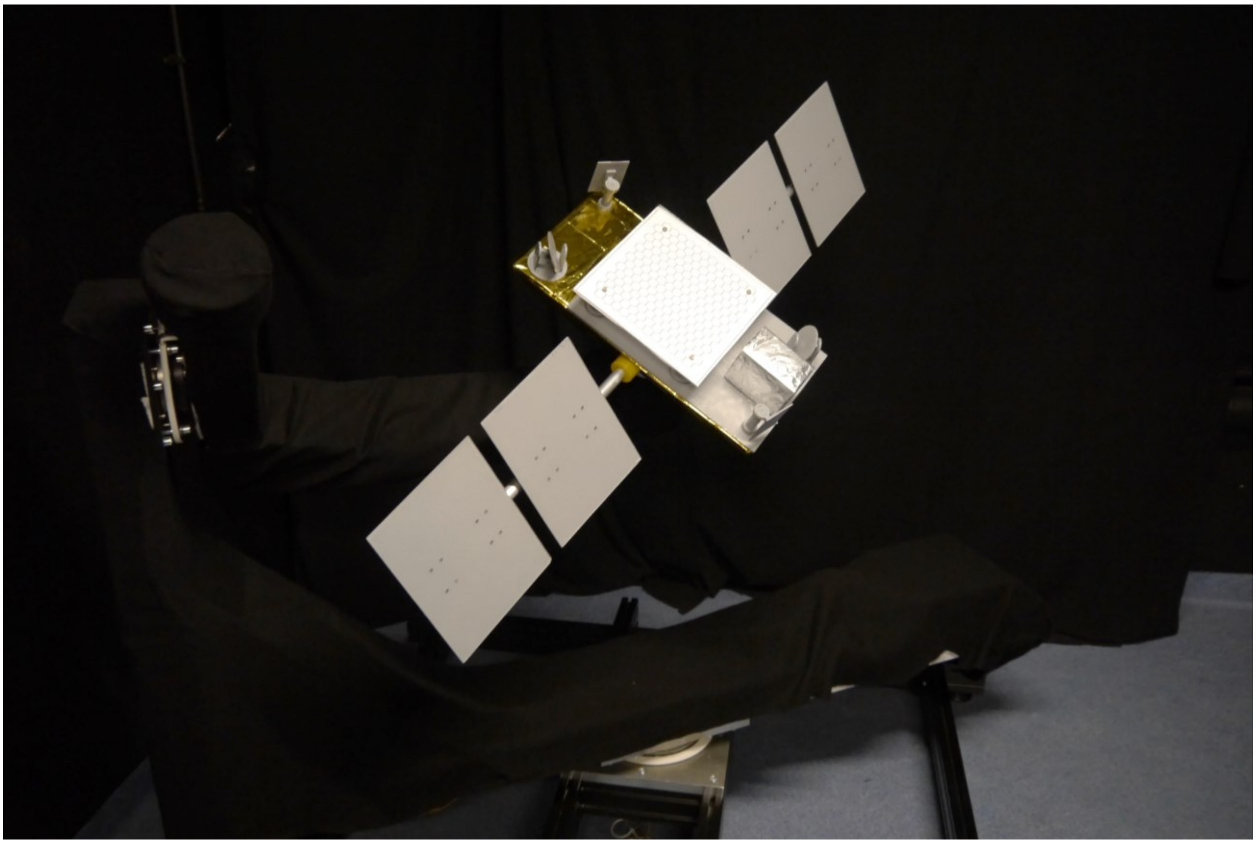

Figure 8. Test-bed based on a dedicated 3 DOF manipulator with target object mock-up.

performed at adequately reduced distance. In fact, performing tests of motion recognition systems on mock-up satellite with reduced scale is a common practice (e.g., [7]).

Links of the mock-up motion system are constructed from off-the-shelve aluminium profiles characterized by relatively low weight and high stiffness. Custom made joints are actuated by Nanotec stepper motors with Harmonic Drive gears for high precision of motion. In joint 1 and 2, additional belt gears for torque transmission from the stepper motor to the harmonic gear are used, while in joint 3 torque from stepper motor is transmitted directly to Harmonic Drive gear by an elastic clutch suppressing vibrations generated by the stepper motor. Rotations of all rotational joints of this manipulator are unlimited. Axes of these joints intersect in a point that corresponds to the target object mass centre (laser beams are used to calibrate the test-bed and assure this with submillimetre precision). Thus, free rotational motion can be easily simulated, as it is composed of rotations around the mass centre. The solution to inverse kinematics problem is, therefore, straightforward. The axes of rotations of the manipulator joints are presented in Fig. 9, where it is shown that they coincide with a single point located at the target object mass centre. The mock-up motion system has to reproduce the tumbling motion of the target object with a maximal rotational velocity of up to 10 deg/s. However, as the 3 DOF manipulator has singular configurations, there are some trajectories that would require infinite velocity of the manipulator joints. The mock-up motion system was designed for maximal joint velocities of up to 50 deg/s, what should be enough for the overwhelming majority of possible trajectories. The trajectories of tumbling motion are checked for maximal required velocity of manipulator joints before the execution of these motions on the test-bed. As an example, velocities of manipulator joints for realization of a trajectory presented in Fig. 1 are shown in Fig. 10.

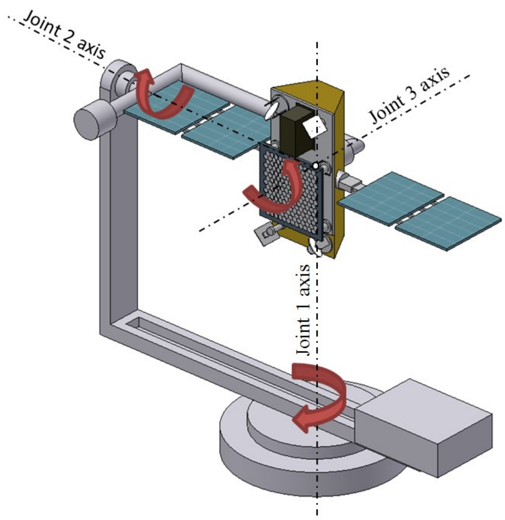

Figure 9. Schematic view of the dedicated 3 DOF manipulator (mock-up motion system) with indicated joint axes.

Although in the presented test-bed all joints have unlimited rotations and links of the manipulator have relatively small cross-sections, the target object mock-up is sometimes obscured by elements of the test-bed. Such situations are unavoidable. Moreover, there are configurations in which even more than 50% of the mock-up is obstructed. Thus, it is necessary to select such parameters of the motion that will not result in significant obstructions of the mock-up during the time of the experiment. A Matlab script was developed to estimate the percentage of the mock-up obstruction during target object motion. Selection of trajectories can be based on, e.g., lowest maximum covered area or lowest integral of the coverage. Such approach limits the set of possible trajectories, but it should not hinder validation of the motion recognition system. A plot showing percentage of area of the target object projection covered by elements of the test-bed during realization of trajectory from Fig. 1 is shown in Fig. 11.

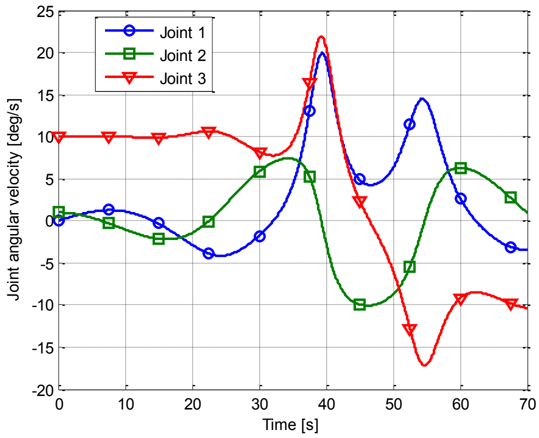

Figure 10. Velocities of manipulator joints during realization of tumbling motion of the target object.

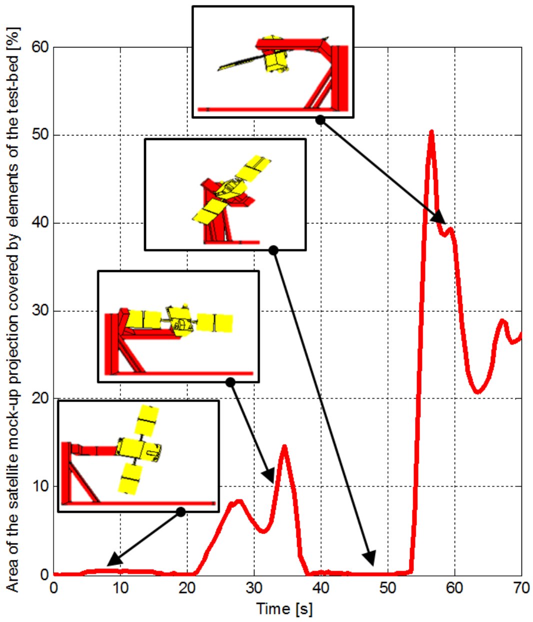

Figure 11. Plot showing what percentage of the target object mock-up is obscured by elements of the test-bed.

All the elements of the mock-up motion system are covered with a black fabric characterized by extremely low reflectivity. The same black fabric is used as a background. As a result, the target mock-up is clearly visible for the motion recognition system, while elements of the test-bed are seen as uniformly black objects. Various lighting conditions can be simulated with a set of lamps serving as a simulator of the Sun. The mock-up of the target object as seen by the motion recognition system camera is presented in Fig. 12. It can be clearly seen in this photo that no elements of the test-bed are visible.

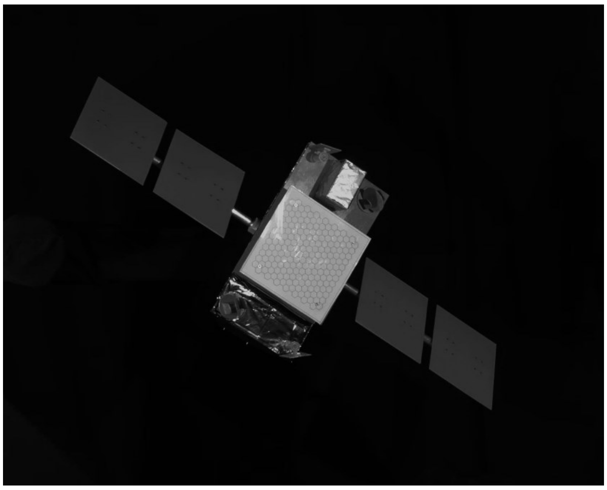

Figure 12. Mock-up of the target object mounted on the dedicated 3 DOF manipulator.

The mock-up target object constructed to be mounted on the 3 DOF dedicated manipulator described herein, could also be used on a planar microgravity simulator that is also available at CBK PAN [8]. This simulator uses planar air-bearings to provide frictionless motion in one plane. The mock-up target object mounted on a base with three air-bearings can move freely on a granite table surface and its free-floating motion can be simulated. Photo of this test set-up is shown in Fig. 13.

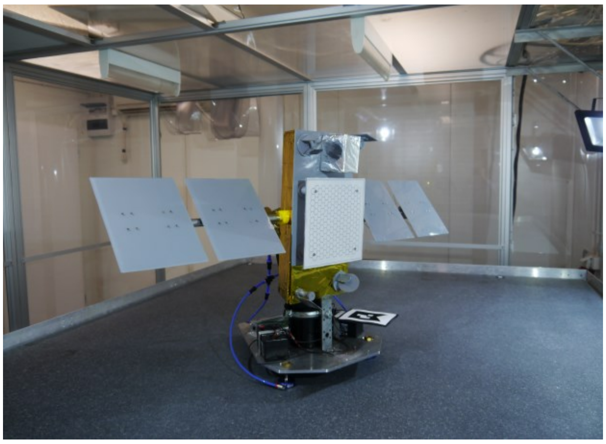

Figure 13. Mock-up of the target object on planar air-bearing microgravity simulator.

5. SUMMARY

In this paper we presented two test-beds developed at CBK PAN in the frame of ESA PECS project no. 4000107934/13 /NL/KML "Robust, unsupervised visual motion recognition of non-cooperative satellite for on-orbit capture" for validation of a motion recognition system. On the first test-bed (called the "virtual" test-bed), the motion recognition system algorithm is tested on an artificially visualized motion of the target object (simulation of view from the motion recognition system camera during on-orbit rendezvous). On the second test-bed, the motion recognition system is observing a scaled mock-up of the target object that is rotated by a dedicated 3 DOF manipulator to simulate rotational motion of a free-floating body. Advantages of presented test-beds were discussed (e.g., unlimited rotations of the manipulator allowing simulation of tumbling motion of the target object for a prolonged period of time). The results of tests performed on these two test-beds during the project will be used for two purposes: (i) to evaluate performance of the motion recognition algorithm in various conditions and (ii) to validate the breadboard of the motion recognition system. The motion recognition system algorithm was already tested on the "virtual" test-bed and now the system is undergoing tests on the 3 DOF test-bed. Both test-beds are versatile and can be used for validation of various visual motion recognition systems.

6. ACKNOWLEDGMENTS

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