TITAN – DEVELOPMENT OF SELF-LIFTING MANIPULATOR FOR ON-ORBIT SERVICING AND DEBRIS REMOVAL

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ABSTRACT

TITAN - "Robotic Arm Development for On-Orbit Servicing Operations" is a European Space Agency project lead by PIAP Space company dedicated to advance the technology of a space manipulator to TRL 6. The TITAN project is focused on development of a manipulator system for performing dexterous operations of repair, inspection and capturing cooperative as well as non-cooperative prepared and unprepared target satellites. One of the distinguishing features of TITAN Manipulator is a self-lifting capability, which significantly facilitates on-ground testing. The aim of the paper is to present development process of TITAN Manipulator – starting with requirements definition and system architecture, followed by analyses, trade-offs and design of key system components and ending with testing methodology.

1. INTRODUCTION

Different concepts of on-orbit servicing missions that utilize robotic manipulator systems are in development at space agencies, as well as, by the industry. [1] First servicing missions were Space Shuttle missions dedicated to repairs and upgrades of Hubble Space Telescope between 1993 and 2009. In case of these missions robotic arm was used mainly to capture and position the Hubble properly and support astronauts performing servicing activities. [2] In 1997 National Space Development Agency of Japan launched a first satellite equipped with robotic arm – ETS VII (Engineering Test Satellite 7), which successfully demonstrate robotic servicing tasks. [3] Other missions including robotic manipulation tasks such as in-orbit assembly or refuelling were also performed e.g. missions to International Space Station or Orbital Express mission. Currently flight demonstrations of robotic servicing technologies are developed in the scope of NASA OSAM (On-orbit Servicing, Assembly and Manufacturing) missions. [2] The range of tasks for robotic systems in space is extensive. The robotic manipulators are particularly considered to be used for following cases:

- On-orbit servicing: Travelling from one spacecraft to another to provide fuel, replace a battery or fix a solar panel,
- Tugging of spacecraft from one region to another: for instance, from low earth orbit to the geostationary orbit, or from Earth orbit to a lunar orbit,
- In-orbit assembly: Assembly of parts of a system, such as attaching an antenna onto a spacecraft on-orbit,
- Debris Removal: Capturing and removing a satellite that has reached the end-of-life and is unable to perform the disposal burns.

Above-mentioned mission scenarios were analysed during development of TITAN Manipulator, especially requirements definition. As the most demanding task was considered capturing of uncooperative satellite.

2. REQUIREMENTS

Project requirements are derived based on ESA requirements, inputs from stakeholders from the industry and review of similar systems. TITAN Manipulator is expected to have a reach of around 1,8 m and capture targets of around 1000 kg. Other analysed use cases include inspection and in-orbit servicing activities.. This results in required control modes like joint-space and Cartesian-space path execution, visual servoing (based on external vision system) and active force/torque control implemented as impedance control. It is required also to test these high-level functions in gravitational environment. While it poses a significant challenge, the tests will be performed in limited scope, with reduced payloads and lowered margins so that the on-ground testing has minimal impact on the design. Testing in 1g conditions leads to significant reduction of mission risk and is considered as major added value by stakeholders interested in the project.

Table 1. TITAN Manipulator parameters.

Parameter	**Value**
Configuration	7 DoF
Length	1,8 m
Force/torque capability	20 N / 20 Nm
Payload (0g)	1000 kg
Payload (1g)	1 kg
Max velocity (Cartesian)	10 cm/s 5 deg/s
Positioning accuracy (2 sigma)	5 mm 0,2 deg
Joint max velocity	5 deg/s
Joint max repeatable torque	372 Nm (Large) 176 Nm (Small)

Figure 1. TITAN robotic arm visualization.

3. ARCHITECTURE

Manipulator consists of 7 hollow-shaft Joints and a Force-Torque Sensor (FTS). It is considered to use a Standard Interface which will allow exchange of the end-of-arm tooling. However, in the scope of TITAN as Standard Interface representation dummy mass is foreseen. The test campaign will be performed with PIAP Space's LARIS Gripper, developed in the scope of EROSS+ / EROSS IOD (within European Union's Horizon 2020 research and innovation programme) [4] and ORBITA (founded by Polish National Centre for Research and Development) projects. [5] [6]

Control architecture is considered to be distributed. Joints perform current and speed motor control, while Motion Controller is responsible for trajectory planning and commanding Joints based on angular velocity. Other modes like joint-level position control or current control are possible.

In the scope of the project, two sizes of Joints (Large and Small) are designed. Each Joint includes a BLDC motor, a Harmonic Drive gearbox, a brake, 2 encoders, bearings and Joint Controller. Joints are connected using redundant CAN bus.

4. ANALYSES

Crucial part of the design process were analyses and trade-offs performed in order to establish design assumptions or support components selection.

4.1. Kinematics trade-off

Kinematic structure of the Manipulator was selected based on analysis of defined criteria such as e.g. reachability, dexterity, folding capabilities, joint loads. In order to evaluate performance of selected kinematic structures preliminary simulations of mission scenario were also conducted. Kinematic analyses were mainly performed by Space Research Centre Polish Academy of Sciences (Centrum Badań Kosmicznych Polskiej Akademii Nauk - CBK PAN). Fig.3 presents two main kinematic structures considered in the project – as baseline was selected structure TITAN II.

Selected kinematics structure allows higher dexterity near manipulator base as well as more compact stowed position and due to lower mass – lower loads acting on joints in on-ground case.

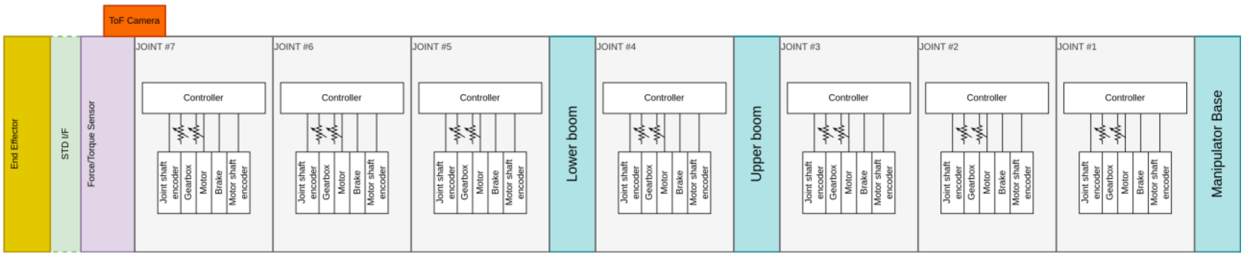

Figure 2. TITAN Manipulator architecture scheme.

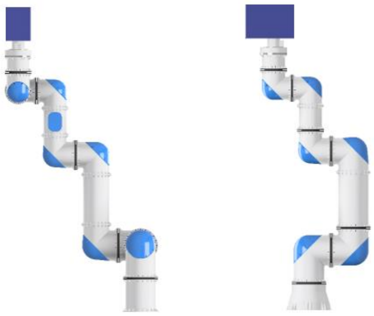

Figure 3. Analysed kinematic structures – TITAN I (left) and TITAN II (right).

4.2. Loads analysis

Loads acting on Manipulator were analysed in order to obtain maximum deliverable Joint output torques required for selection of drive system components. Cases taken into account for evaluation included maximum loads from mission scenarios, as well as 20 N of force and 20 Nm of torque applied at Manipulator's tip simultaneously. As loads acting on Manipulator during on-orbit operations and on-ground tests are significantly different – both cases were carefully examined. However, actuation assessment for on-ground case utilized reduced motorization factors in order to limit oversizing of the robotic arm. On-ground peak Joint torques were derived based on test trajectories and Manipulator deployment from Stowed to Deployed configuration. Since the on-ground loads are significantly higher than in in-orbit case it was proposed to limit Manipulator workspace during on-ground operations to cylindrical volume of 0,6 m radius. It prevents Joints' overloading and allows to perform necessary tests. Tab.2 presents comparison of required Joint torques for in-orbit and on-ground case (with limited workspace).

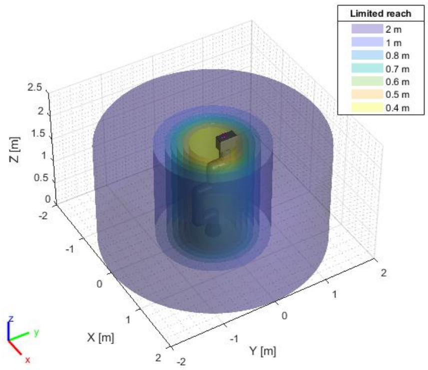

Figure 4. Visualization of manipulator workspace limits.

Table 2. Ranges of maximum required joint torques.

Range of maximum required joint torques	
Case	Torque range [Nm]
On-orbit continuous torque	~ 2,5 – 7
On-orbit peak torque	~ 20 – 60
On-ground torque (in limited workspace)	~ 0,1 – 210

4.3. Velocity analysis

An analysis was conducted in order to calculate Joint velocities required to ensure specified tip velocity. Joint velocities assessment was performed for random Manipulator configurations in full and limited workspace using the Moore-Penrose pseudoinverse of Jacobian. Tab.3 below shows percentage of Manipulator configurations which allow to achieve tip linear velocity in z-axis of 0,1 m/s and angular velocity of 5 deg/s.

Table 3. Summary of joint velocities analysis.

Workspace range	Percentage of configurations with ensured required maximum tip velocity
Full workspace	91 %
Limited workspace 1,4m < Z < 1,7m	87 %
Limited workspace, Cylinder R=0,6m 1,4m < Z < 1,7m	89 %

4.4. Structural analysis

Mechanical structures of Manipulator and Joints were modelled with FEM and checked against random and sine vibration as well as static, quasistatic and thermoelastic loads. Additionally, influence of shock response spectrum was evaluated. Launch loads are transferred into the system in Stowed configuration via Manipulator base and 5 launch locks (represented by dummy structures, as HDRMs are out of the scope of the project). Projected 1st natural frequency of the Manipulator equals to 206 Hz in hard-mounted condition, what exceeds required minimum value of 110 Hz by a safe margin. Loads derived from random environment were identified as critical for the mechanical design and thus used for evaluation of Joint bearings in CABARET software. Furthermore, envelope of operational loads (in-orbit and on-ground) seen by Joints was derived and applied to Large and Small Joint FEM models. Check was successfully passed.

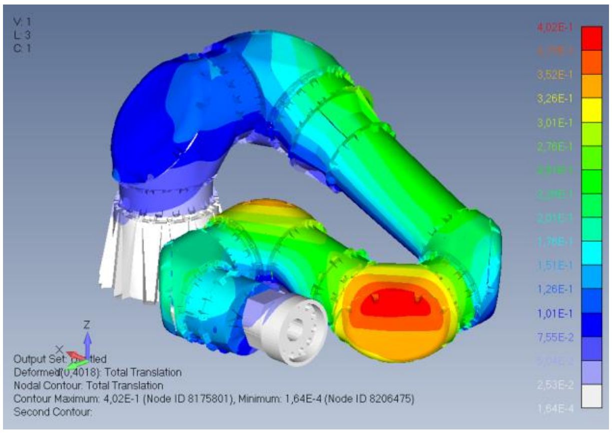

Figure 5. Mode 1 at 206 Hz.

4.5. Positioning accuracy analysis

To examine control system performance an analysis of Manipulator positioning accuracy for selected control modes was conducted. Accuracy analysis includes determination of error parameters according with ECSS-E-ST-60-10C such as Absolute Performance Error (APE), Absolute Knowledge Error (AKE) and Repeatability Error.

Analyses were performed for Velocity Control mode and Position Control mode using model of a single non-linear Joint, while in case of Cartesian Control mode was used complex multibody model of Manipulator. Prepared control model does not include electrical part of the system – current loop performance in not analyzed. Joint model contains mechanical part of motor, Harmonic Drive gear, bearings and output inertia. Model includes nonlinear effects such as input and output shaft bearings friction torque obtained from analysis in the CABARET software and Harmonic Drive gear stiffness. Error of measurement sensor – encoder is also taken into account and defined as uniform distribution with maximum value of 0,01 ° (catalogue value).

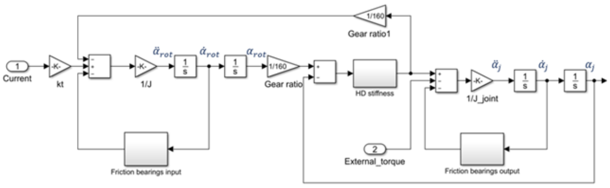

Figure 6. Joint model in Simulink.

Conducted positioning accuracy analysis includes examination of system response for different conditions: specified set-point change and external torque step change. Additional accuracy analysis was conducted for in-orbit conditions simulated by pre-grasping phase trajectories. Fig. 8 shows exemplary analysis results – maximum values of performance error obtained for Cartesian Control mode simulations.

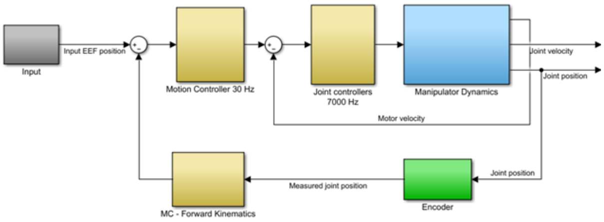

Figure 7. Cartesian control mode scheme.

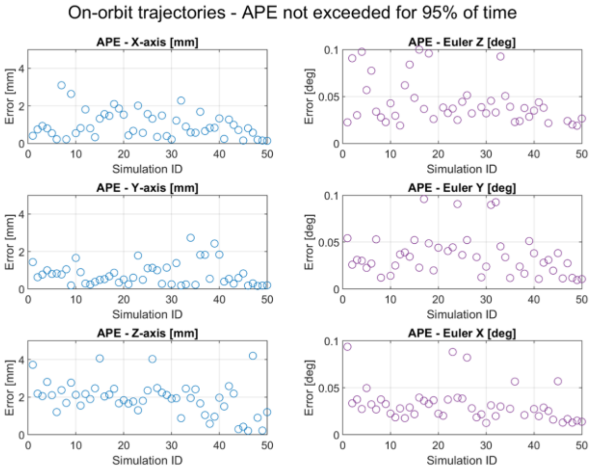

Figure 8. Maximum APE values for on-orbit trajectories analysis.

Calculation of Repeatability Error of Manipulator in Cartesian Control mode for set of test trajectories was performed. Repeatability was defined as the deviation from the mean error computed for a set of samples (N=10 in case of conducted analysis) taken at the same desired position.

In all analysed cases performance error for 95% of trajectory time was lower than 0,1 deg and 5 mm. Knowledge error did not exceeded 0,05 deg and 0,6 mm and repeatability was better than 0,1 deg and 1,7 mm.

5. DESIGN

5.1. Mechanical design

TITAN robotic arm design is based on 3 Large and 4 Small Joints used to actuate movement of the structure. Introducing a family of 2 different Joint sizes can be seen as a compromise between limiting design complexity and mass/performance optimization. Sharing architecture between actuator family members allows for modularity and scalability required in the robotic arm design. Key building blocks of each Joint are: TQ-Robodrive BLDC motor, Harmonic Drive gear from CPL-2A series and 2 pairs of bearings in back-to-back configuration supporting input and output shaft. In order to enhance Joint stiffness each bearing pair was separated with set of precision spacers. Rotation of input and output shafts of the actuator is controlled and reported by Netzer absolute encoders. Holding function as well as emergency stop can be executed due to presence of electromagnetic brake placed on the input shaft. Joints 2, 4 and 6 are additionally equipped with heaters adjusting the temperature of robotic arm and matching sensors. It should be also noted that actuators are used as a support for Joint Controller unit. Due to hollow shaft design Joints enable routing of the harness through the mechanism.

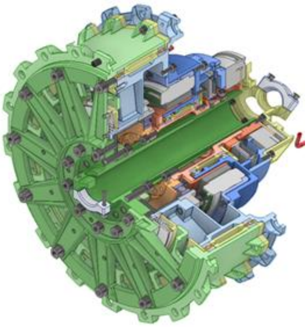

Figure 9. Joint structure.

Joints are connected with each other with mechanical structures called Booms. Booms are designed in different shapes (angular or straight) and sizes, however their geometry was strongly influenced by kinematic, stiffness and mass requirements. Besides the interfaces for connection with Joints stator and rotor, they also provide Dummy HDRM interfaces, Joint Controller interfaces and enable safe cable harness routing. For easy access during assembly and maintenance, angular Booms are also equipped with removable Lids placed on Boom's bends.

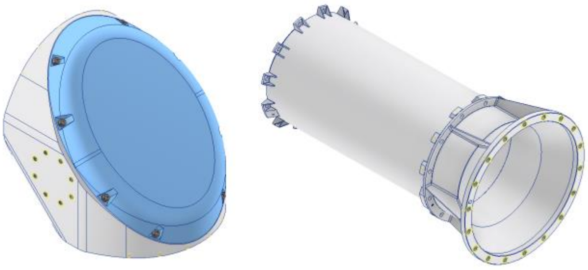

Figure 10. Angular Boom with Lid (left) and Straight Boom (right).

After HDRM release (or detachment from Dummy HDRMs in case of TITAN EM) the only connection of the robotic arm with Spacecraft is through Manipulator Base.

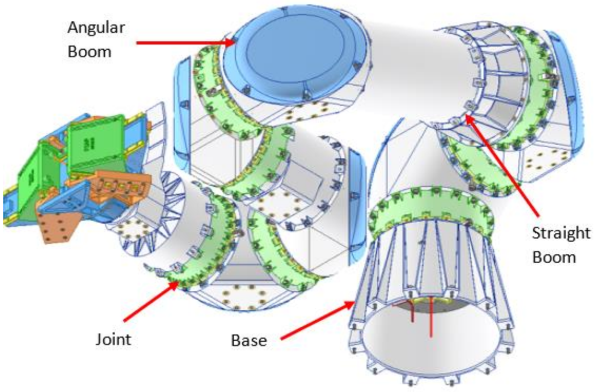

Figure 11. TITAN Manipulator in Stowed configuration.

In order to optimize mass and strength properties of Booms and Joints, most of their mechanical structures is produced from aluminium.

5.2. Electronics design

The harness are routed through Joints hollow-shafts and include CAN bus, power supply, temperature sensing, heaters and safety wire (grounding). The actuators are controlled by Joint Controllers modules designed by Space Research Centre Polish Academy of Sciences (Centrum Badań Kosmicznych Polskiej Akademii Nauk - CBK PAN).

Thermal Control System (TCS) is developed by Spacive company and consists of heaters, temperature sensors, coatings and MLI, which cover outer surfaces of robotic arm structure.

The Manipulator will be also equipped with the Force-Torque Sensor developed in separate PIAP Space project - ORBITA, similarly as the Vision System used during tests. [7]

Some details of the above-mentioned components are presented hereunder. The harness is routed throughout the whole robotic arm, with each Joint having separate wires for power supply. Joints equipped with heaters and temperature sensors also have wires of these components separated. The CAN bus wires are twisted pair, for each Joint it goes into and out from the Joint Controller.

Joint Controllers designed by CBK PAN are suitable for environmental tests such as shock, vibration, thermal-vacuum and EMI. PIAP Space has developed additional set of controllers with similar functionality – motor control, brake control, encoders and temperature reading. PIAP Space's Joint Controllers are based on COTS motor controllers. PIAP Space's JC has the same electrical and mechanical interface as CBK JC but different SW interface.

Force-Torque Sensor is controlled via CAN bus and sends data through this bus. Its accuracy is estimated to be equal to force-torque to voltage converter due to usage of sophisticated delta-sigma ADC making the electrical measurement error negligible. The accuracy class of force-torque analogue sensor is 0.2%. The digital part does not worsen this result.

For the needs of testing a compact EGSE cabinet will be developed. Its foreseen components are Robotic Arm Controller (RAC) board, set of relays for switching on/off the power supply for particular joints and devices, controlled by RAC board, 3kW power supply for the robotic arm actuators and a PC.

5.3. Control System and Software design

The modules responsible for control and operation of the Manipulator are Robotic Arm Controller (RAC) and Motion Controller (MC). The main tasks of the RAC include data exchange management between the MC and other actuators via CANopen protocol. Moreover, it is responsible for commands execution and monitoring parameters of Manipulator. It provides protection functions e.g. against motor overload, overcurrent etc. The system is based on ARM Cortex-M7 MCU (Microcontroller Unit) with the software written in C language. On the PCB (Printed Circuit Board), there are relays to control voltage of the entire robotic arm.

The MC is a part of the EGSE software and it is responsible for trajectory planning, collision avoidance and Manipulator control. In the System, there are implemented control modes such as Position Mode, Cartesian Control Mode and Active Force/Torque Control Mode. Control algorithms for the MC have been developed and tested during simulations by CBK with usage of MATLAB/Simulink environment. [8] The implementation is performed by PIAP Space using automatic code generation tools included in the same software.

To provide control and test capability for Manipulator, EGSE software was developed as a part of functionally complete robotic system. The software is a set of independently running applications written in C/C++ language which carry out the tasks of the motion control, human machine interface and data recorder. The software manages internal communication and provides synchronization for the data transfer.

All control systems with their software ale developed in accordance with the Company's CICD processes and tailored ECSS guidelines.

6. TESTS

The test campaign of the EM includes functional, performance, environmental and life tests. The joint-level tests allow verification of the performance in wide range as needed for in-orbit and gravitational loads. The crucial characteristics are maximum velocity, exerted torque, stiffness and control accuracy. The environmental test campaign of Joint include shock, EMC, test campaign in thermal vacuum chamber (thermal balance, thermal cycling, functional and life test). The vibration tests will be performed on the whole Manipulator. Performance characteristics will be also gathered on an air-bearing table to simulate non-gravitational conditions.

In the scope of TITAN project, three models were introduced: Joint Development Model, Joint Engineering Model and Manipulator Engineering Model. Joint models were chosen as main building blocks of Manipulator. DM and EM Joints will be of Large Joint size.

Engineering Model will be used during Manipulator tests including demonstration of a target capture. The demonstration will be performed with EM Manipulator, Vision System and Gripper. Manipulator will be controlled from EGSE and will capture the LAR of a satellite dummy.

CBK Joint Controller will be used in tests on joint level, air-bearing tests and in the environmental tests (vibrations, shock, EMC, TVAC). The PIAP Space's Joint Controller will allow functional test of Manipulator.

The vibration tests of the Manipulator will be performed with 2 Joint Controllers and 5 structural dummies of the Joint Controller. The EMC tests are not foreseen on Manipulator level. However, conducted emissions and susceptibility tests will be performed on Joint level and Force/Torque Sensor.

The performance test of Joints verify maximum torque, maximum velocity, torque-velocity envelope, backdrive characteristics and control performance in all developed modes (position, velocity, current), braking, low-speed performance.

Manipulator movements require Joint actuation in wide range of speeds and torques. That is why the velocity-torque envelope (including backdrive) is used as main performance characteristics. Also, potential reuse of parts of the project outputs may base on developed Joints.

The functional tests of Manipulator will be focused on tracking and capture of a dummy satellite with LAR, but will include also accuracy verification with CMM. The accuracy is one of the most important factors during capture process. The better the alignment of the gripper and captured LAR, the lower forces are acting on the gripper jaws.

Manipulator is able to move in limited workspace based on Joint torques. The dummy satellite with LAR will have gravitational offloading.

The tracking and capture testing will be performed with Vision System developed in the scope of PIAP Space's ORBITA project [7] and PIAP Space's LARIS (LAR Gripper developed in the scope of EROSS Plus project) [6].

DM Joint tests were already performed. Joint velocity-torque performance was verified successfully. General DM Joint design feasibility was confirmed. Areas for further development were identified and include mostly JC software.

Figure 12. Assembled Development Model of Joint.

7. SUMMARY

TITAN EM design and analysis phase has been closed. Currently mechanical components are being manufactured and software implementation is in progress. It is planned that Engineering Model tests will start in the last quarter of this year.

8. ACKNOWLEDGMENTS

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