GROUND TESTS FOR ON-ORBIT SERVICING OF A GEO SATELLITE FLEET

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INTRODUCTION

The On-Orbit Servicing of a fleet of geostationary satellites was analysed in an ESA funded study named Satellite Servicing Building Blocks (SSBB). The study team was led by EADS Astrium; general background and results have been presented previously in the 2006 ASTRA workshop [1], and in the 2008 ASTRA workshop [2]. The focus of this paper is on the robotic aspects, and more specifically on the new SSBB gripper design and specific ground test results.

In the study, several alternative on-orbit servicing concepts were identified, and analysed for their rationale, impact on the client satellite design and the user constraints. Based on the servicing tasks identified, several servicing system architectures have been defined and assessed. Each Servicing System Architecture included a servicing scenario, a servicing vehicle concept, logistic re-supply elements such as specific containers, launcher(s) and a ground segment.

For one selected candidate architecture, providing scheduled and unscheduled maintenance to a fleet of GEO satellites, the impact of the client satellite configuration and economical attractiveness were further assessed. Many exchangeable elements were identified which led to the definition of various types of smaller and larger Orbit Replaceable Units (ORUs) representative for the large GEO telecom satellite class. The next step in the study was to define and size the robotic means to support the various in-orbit maintenance scenarios, the mode of control for the robotic system, a review and trade-off of gripper and grasping fixtures, and the identification of necessary connectors and mechanisms.

For one representative ORU, an on-board computer module, a 1:1 scale mockup was built was study team partner Austrian Aerospace. A new gripper was designed and built by Dutch Space and Heeze Mechanics, a small Dutch high-tech engineering company. ORU insertion tests were performed with an industrial robot in the robotics laboratory at the KU-Leuven. The higher level test control system was built by Trasys.

ROBOTIC SYSTEM REFERENCE DESIGN

The robotic system reference design was driven by the servicing configuration, in particular the location of the ORUs on the client satellite, and the wish to minimise the design impact on the client satellite. As the servicing vehicle concept was designed to dock with the apogee kick motor, on the zenith pointing side of the client, a payload mounted at the other (earth pointing) side of the client, would require a very long arm.

Based on the servicing system requirements, the reference robotic system concept selected was a single, relatively short arm mounted on a ring structure on the docking module so that the could be positioned below the client satellite in an adequate position for a servicing operation. The position along the ring is chosen such that it optimises the access to ORUs both on satellite and to the servicing vehicle cargo bay and thus minimises both the transfer time and the required length and mass of the arm. Reference designs for the arm concept were arms from the ESA ERA, Eurobot and DEXARM projects.

During the study, both kinematic and dynamic aspects of robotic servicing were investigated. The first step was to evaluate possible access corridors. This allowed us to make a first selection of candidate robots systems. Robotic systems considered in the evaluation ranged from arm type robots (similar to the Space Station Remote Manipulator System SSRMS and the smaller European Robotic Arm ERA) and a “free roving” 3-armed robot (similar to Eurobot).

Access corridors were investigated using 3D CATIA models of both the client satellite and the servicing vehicle. An evaluation was made of the free space available for a robot system to move around and reach the different places of interest on both the client satellite and the servicing vehicle (for spare part storage). A preliminary kinematic validation was done with ROBCAD. A rough Collision Avoidance model was constructed from basic shapes such as boxes and cylinders to create convex hulls around the client satellite and servicer structures. Antenna reflector dishes and solar arrays (initially modelled as swept volumes) represent large obstacles that can block access to payloads. It was found that in some cases, to reach a payloads located in the top half of the client satellite, the rotation of a solar array might have to be stopped to provide sufficient access. The Eurobot solution appeared to have some more impact on the design of client satellite, requiring a series of handrails, dedicated fixtures or sockets (supporting locomotion) to be placed on every potential client platform. It was also found that dedicated (re-)design of ORUs on the (earth pointing) top-side of the client satellite would be necessary such ORU easier to access and hence serviceable on-orbit.

From the robot dynamics point of view, a lot of attention was given to the detailed mechanical design of both gripper – grapple fixture combination and the ORU guidance during insertion. Many ORUs were found to fall in the category ‘square peg-in-hole’ insertion. The on-board computer module selected for breadboard testing falls exactly in this category.

THE SSBB GRIPPER

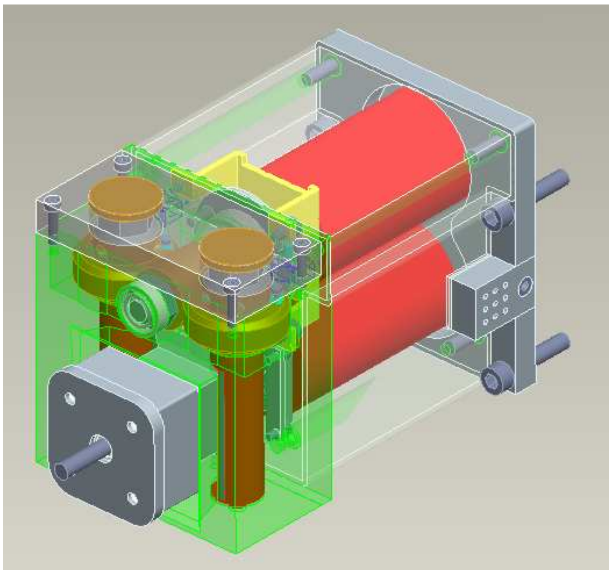


Figure 1 The new SSBB Gripper

For the SSBB study Dutch Space together with supplier Heeze Mechanics designed and built a new prototype gripper, and accompanying grapple fixtures. The gripper and grapple fixtures were designed to allow a robot to handle a large range of ORU’s. The grapple fixtures are to be mounted on each ORU. Fairly early in the study, the team decided to standardise the grapple fixture to the standard microsquare fixture [5], already in use on the International Space Station The gripper has mechanical design features to match the grapple fixtures and allows the robot arm to manipulate the ORU’s.

The gripper is also designed to have an integrated a “screwdriver” that can mechanically actuate a socket inside a grapple fixture. The socket can then drive mechanisms, for example a latching mechanism, or a connector mating mechanism.

Key requirements for the new SSBB Gripper

Requirement	Value
Capture Range	> 6.5 mm / 8.7 mrad
Interface Strength	> 222 N / 150 Nm (including a safety factor of 1.5)
Interface Stiffness	> 170 N/mm / 86 Nm/mrad
Actuation Torque	> 10 Nm peak, 5 Nm continuous
Gripper Dimensions (Length And Diameter)	< 120 x 120 x 182 mm (requirement)

Table 1 Key Requirements for the new SSBB gripper

Cam-lock principle

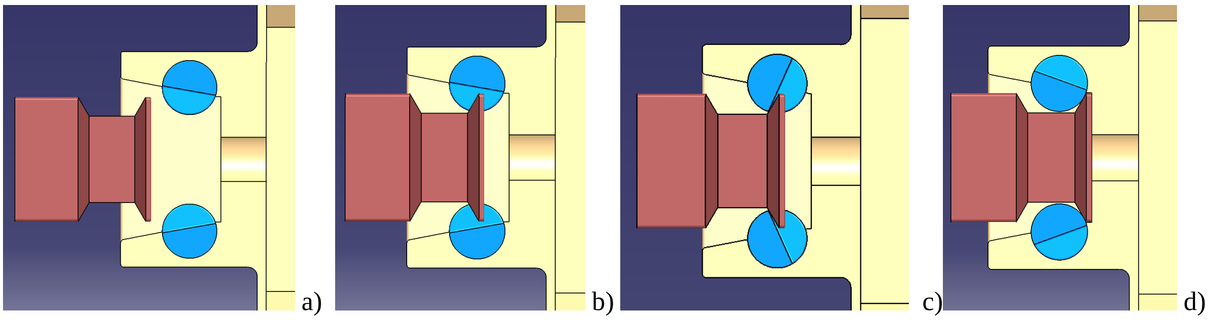


Figure 2 CAM-Lock Concept

The Cam-lock principle offers an elegant way of establishing a stiff contact by pulling the fixture in. In Figure 1Figure 2a, the gripper is positioned in line with the microsquare grapple fixture (MS, brown) and the nose of the gripper housing is slowly moving over it. The tapering of the nose opening (a square crater) increases the capture range of the gripper and will guide the MS to its intended position.

In Figure 1Figure 2b, the MS has been pushed deep enough inside the nose of the gripper to allow the cams (blue) to start closing. In practice, the robot will drive the gripper as deep over the MS until the crater bottom touches the top of the MS and a certain push in force threshold is exceeded.

In Figure 1Figure 2c, the cams have rotated about 90 degrees, and the microsquare grapple fixture can no longer escape from the gripr. The pull-in configuration allows the gripper to generate relatatively large alignment forces and torques and pull itself closer over the MS. In this way significant misalignments can be overcome.

In the In Figure 1Figure 2d, the cams have rotated further. The MS is pressed against the crater bottom with significant pretension. The pretension forces must be high enough to avoid gapping of the MS when loaded to the required maximum force or torque.

The advantages of the cam-lock principle are:

- Very short load path. This results in a strong yet small design.
- Few moving parts. This increases the reliability of the gripper.
- Generates relatively large forces / torques because it *pulls* the microsquare into the nose.
- Adequate capture range

Many design details were analysed in depth during the study. One of the more critical issues was found to be the selection of the cam material. The cams have to be high strength, non corrosive, wear resistant and exhibit a constant friction coefficient.

The cams are wedged between the microsquare fixture and the gripper nose housing material. The contact area between the cams and the nose housing is large enough to keep the stress at a low level (~20 N/mm2). However the contact area between the cams and the microsquare fixture is much smaller. The induced stress (Hertz) is now about 521 N/mm2. Therefore the selected material for the cams is high strength stainless steel: 15-5PH

The screwdriver assembly consists of a screwdriver house that contains a torx screwdriver head that is pushed out by a pop-in spring. The spring is not drawn in the figure. The torx head fits into a torx screw socket in the microsquare.

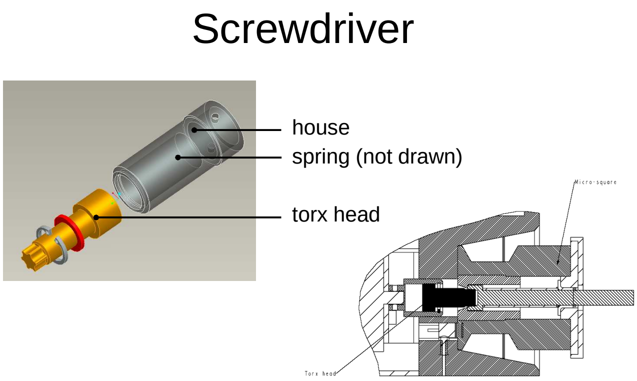
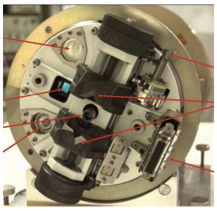
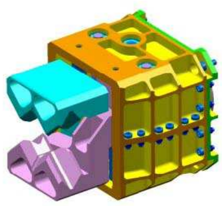
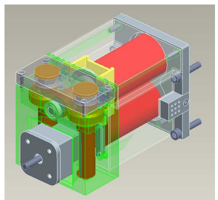


Figure 3 Integrated screwdriver concept

The gripper design has gone through several optimisation iterations. In the final design, we were able to reduce the overall dimensions significantly to (height x length x width) to 150 x 100 x 90 mm. Compared to the Eurobot gripper [4] the volume was decreased from 2.6 to 1.35 l, almost a factor 2. This was mainly possible by using new Maxon flat motors with built-in Hall sensors.

It is interesting to compare the gripper against two other grippers that were designed to grapple microsquar fixtures: the OTCM (ORU Tool Changeout Mechanism) that is the end-effector of the SPDM (Special Purpose Dexterous Manipulator), and the Eurobot gripper, see Table 2 In the table the new gripper is called SSBB gripper. The OTCM is the strongest but also by far the largest. The SSBB gripper is smallest (a factor 2 smaller volume than the Eurobot gripper) and still very strong (a factor 1.5 higher maximum load torque than the Eurobot gripper). This is possible because of the cam-lock principle that has a very short load path. The OTCM and Eurobot gripper however can exert much higher actuation torques than the SSBB gripper. It must also be noted that the OTCM and Eurobot gripper can also grapple H-fixtures while the SSBB gripper cannot.

Table 2 Comparison of three microsquare grippers

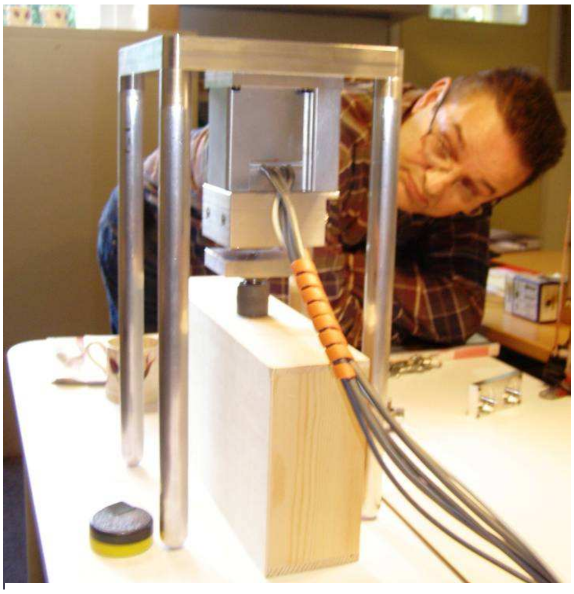
	OTCM [5] 	Eurobot gripper [4]) 	SSBB gripper 
dimensions [mm]	Ø 267 x > 400	180 x 120 x 120	150 x 100 x 90
volume [l]	22	2.6	1.35
strength (max load torque) [Nm]	339 Nm (incl. safety factor of 3)	102 Nm (incl. safety factor of 3)	150 Nm (incl. safety factor of 1.5)
actuation torque (screwdriver) [Nm]	34 Nm (68 Nm peak)	34 Nm (82 Nm peak)	4.6 Nm (7.5 Nm peak)

GRIPPER STAND ALONE TESTS

Test setup

Stand-alone tests were performed on the gripper in 3 different test setups. The main test support tool was a rig with 4 legs (poles) in which the gripper could be mounted horizontally or vertically. The vertical position with the gripper nose (crater) facing down was used in nominal and misaligned grapple tests, the pull-out stiffness test and in an additional grapple test under load. The vertical position with the gripper nose (crater) facing up is used in a screwdriver torque test. Finally, a horizontal position is used in a holding momentum (stiffness) test

Figure 4a Horizontal gripper test setup



b) Vertical gripper test setup

Test procedure

The stand-alone tests on the gripper included a wide range of tests, including visual inspection, accuracy tests, communication tests, pull-out stiffness and bending stiffness. The screwdriver subsystem was tested for pop-in, torque and speed control.

Test results

All tests were run according to plan and were completed according to schedule. The test data gathered was complete and contained no obvious malfunctions. The grapple function was demonstrated to be able to cope with relatively large misalignment and also able to “pull-in” the grapple fixture under relatively severe misalignments The screwdriver function was shown to pop-in successfully under misaligned conditions and could be controlled in current mode (directly proportional to the screwdriver output torque) as well as in position mode (number of revolutions).

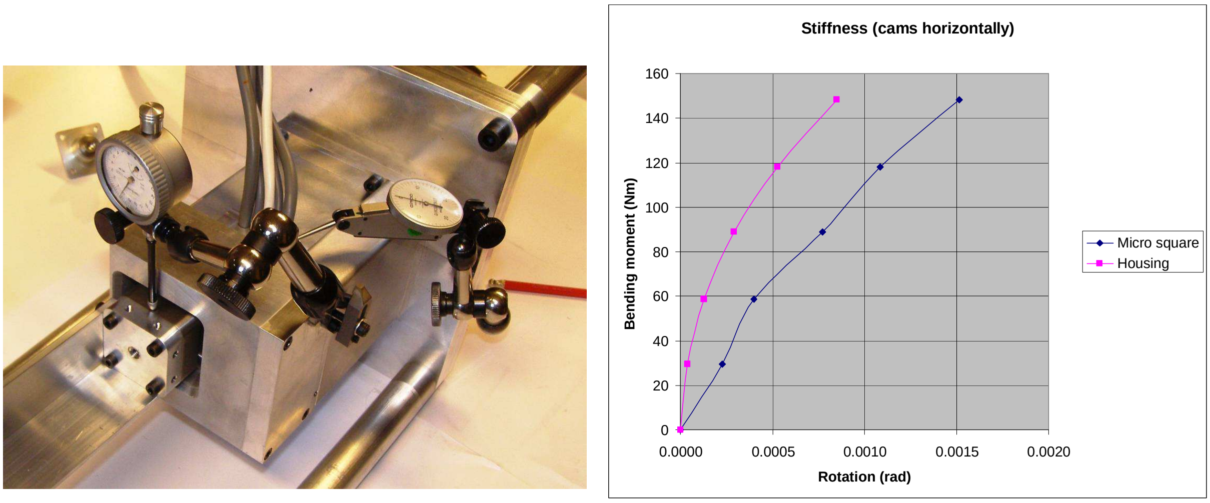


Figure 5 Setup and results of the bending stiffness test

SYSTEM LEVEL TESTS

After the stand-alone tests, the gripper was shipped to KU-Leuven and integrated with the testbed (see Figure 6). The gripper was mounted on a Staubli industrial robot with four simple bolts, and the cabling was gripper cabling guided on the side of the arm. The gripper motor controllers (Maxon EPOS) were mounted on a board to the side of the robot. Grapple fixtures were mounted on the test ORU.

An important challenge was to integrate the low level gripper controller with the supervisory control system. The testbed control architecture was designed to have three-tiers: Low level control in the continuous time domain, Middle level control in discrete time, where low level actions are specified and initiated, and Higher level, where Middle level compound actions are planned and strategies executed. A clear mismatch was found between the functionality and autonomy expected from the gripper controller by the Middle level controller, and the level of functionality and autonomy provided by the EPOS controllers. The standard EPOS controllers come with a user friendly standard windows user interface. This is adequate for testing and debugging motor level control issues. But we found that there is a big step from a motor level driver for a gripper motor, to creating elementary but autonomous gripping functions. Gripper functions have to take into account various start and stop criteria, based on motor torque, time, position and dedicated external micro switches.

Figure 6 The SSBB gripper in action in the testbed at KU Leuven

A dedicated gripper driver was developed, using the EPOS command library and running on a dedicated Windows PC. The driver was essential in translating commands from the Middle control level working in discrete time into the continuous time domain of gripper control loops.

CONCLUSIONS

- As part of the Satellite Servicing Building Blocks (SSBB) study, a new gripper concept was developed
- The new gripper design features a simple and robust design
- The new gripper is very compact, and fully compatible with microsquare fixtures
- The gripper was successfully tested in both stand alone and in system level tests
- All key requirements have been met: grapple range, strength, stiffness, actuation torque
- In the design of complex robotic systems, careful attention has to be given to the integration of the lower control levels, especially the functionality and autonomy expected in the link between discrete (command) level and the lower continuous time level.

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