Design and evaluation of an end-effector for a reconfigurable multi-robot system for future planetary missions

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Abstract— **This paper presents the design, functionality, and evaluation of an end-effector operating at the end of a 6 degree-of-freedom manipulator of the existing planetary rover SherpaTT. The end-effector consists of an active electro-mechanical interface (EMI) which has an active mechanical docking interface, as well as power and data connectors, a camera primarily used for visual servoing, and LED lights. The ability of the end-effector to grapple different robotic systems and change their configuration is proved under laboratory and field conditions in the framework of a heterogeneous multi-robot system. The end-effector of SherpaTT is an improved version of the previous end-effector of the predecessor project RIMRES. This paper outlines the development process and improvements of the end-effector and describes its role within different terrestrial test scenarios in more detail. Learned lesson will help to develop the end-effector in the H2020 EU-funded project SIROM (Standard Interface for Robotic Manipulation of Payloads in Future Space Missions) which will be deployed at the manipulator of SherpaTT for experimental verification for future planetary missions.**

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1. INTRODUCTION

The interest to explore celestial bodies of our solar system and to do in-situ science makes the use of robotic systems for exploration indispensable. A very promising option for realization of a planetary exploration is a group of heterogeneous robots (forming a Multi-Robot System (MRS)), being able to interact with each other. Specialized agents in the team are able to solve different tasks such as sample taking, sample transportation or exploration for scientifically interesting spots more efficiently than a single system equipped for all parts of a mission.

Within the project TransTerrA a modular robotic system for semi-autonomous cooperative exploration of planetary surfaces including the installation of a logistics chain was developed [1]. In order to achieve these objectives the robots are designed to be augmented with modular elements for different exploration scenarios, which can be additionally controlled by humans using a man-machine-interface. The experiences, gained through the predecessor project RIMRES [2] allowed to improve the development of the robotic systems in TransTerrA.

The main mission scenario is to extend the exploration capabilities and handle complex mission tasks by introducing a heterogeneous team of robots. This team consists of mobile and immobile robotic elements including the rovers SherpaTT [3] and Coyote III [4] which are able to establish a logistics chain using immobile elements in the form of a BaseCamp (stationary module) as well as portable modular payload-items (PLIs). To establish the logistics chain, all robotic systems are equipped with at least one modular electro-mechanical interface (EMI) [5], allowing to connect the different systems with each other using a male part ("passive") and a female part ("active")[2].

An end-effector on the manipulator arm [6] of SherpaTT (Figure 1) is used for handling of PLIs, as well as a BaseCamp. The end-effector performs tasks such as grasping of dynamic loads of up to 250 N, static loads of up to 450 N, and establishing an electrical connection for data and power transmission. LED lights and a camera embedded into the end-effector help to control the manipulator when operating autonomously with visual servoing to support the docking operation. A force torque sensor (FTS) mounted between the manipulator‘s last joint and the end-effector allows force / torque monitoring during the docking process. One highlight of the end-effector is the ability of visual servoing with one or more docked payload-items on the end-effector. Every PLI is provided with a female EMI, which enables communication between the systems. Thus, with docked PLIs effectively the last docked PLI serves as end-effector of the manipulator arm.

The following sections of this paper present: First, a short review on related work within the context of end-effectors. Second, a description of the structure and core elements of the end-effector with highlights of improvements compared to the previous end-effector design. Third, a description of end-effector operations. Fourth, a proof of concept during experiments and function tests and fifth a conclusion and

[2]Video with overview on conducted experiments available at: `https://youtu.be/pvKIzldni68`

Figure 1. End-effector mounted on the manipulator arm of SherpaTT

outlook for further work, finalizing this paper.

2. RELATED WORK

In robotics an end-effector is a device at the end of a manipulator arm, designed to interact with the environment. End-effectors may consist of tools or, e.g., an interface for connections. This section describes existing end-effectors in space, industry and modular robotics.

The most known end-effectors are used on industrial robot arms [7], [8]. Grippers are the most common type of end-effectors. They can use different gripping methods and actuation styles [9], without additional tasks like transfer of power supply or data transfer to the grasped subsects. Other end-effectors use material removal tools for cutting, drilling and deburring. End-effectors on industrial robot arms only grasp objects without fixing them with a latch mechanism.

End-effectors in space are well tested with a long lifetime [10], [11]. One robotic end-effector for the International Space Station (ISS) is the so called Orbit Replaceable Unit (ORU)/Orbital Tool Changeout Mechanism (OTCM). Its task is to handle the ORUs equipped on the ISS for routine maintenance. The OTCM Emulator consists of a gripper mechanism, a video system for viewing the Dexterous Handling Target and for guiding the OTCM Emulator gripper, as well as a socket advance/retract mechanism[12]. The Latching End effector (LEE) is attached to the two ends of the Space Station Remote Manipulator System which is mainly used for the ISS assembly [13],[14]. The LEE can perform soft capture and rigid docking and provide an electrical connection for power and data across the end-effector/payload interface. An other end-effector, applicable for orbital servicing is the end-effector for self-relocation of a space manipulator[15]. The Self-Adapting Robotic Auxiliary Hand (SARAH) is also one end-effector for operations on the ISS [16].

The Instrument Positioning System (IPS) within the Instrument Deployment Device (IDD) is used as an end-effector by the Mars Exploration Rovers (MER)[17]. Its task is to place and hold in-situ instruments for collecting science data.

In modular robotic systems like the Automatic modular assembly system (AMAS)[18] and the Intelligent Building Blocks Concept for On-Orbit Satellite Servicing (iBOSS)[19] a manipulator with end-effectors is used to exchange modular cubes.

The end-effector presented in this paper goes a step beyond. It is usable within a multi-robot system for future planetary applications which allow changing of a mission scenario of interaction between different robots. With its integrated camera it can support visual servoing for docking and after docking to a robot system it can transfer power and data via its electrical connections. Through its standardized interface the end-effector can support different tasks, e.g., ranging from simple pick and place operations to soil sampling by relying on an attached sampling module.

3. STRUCTURE

The end-effector at the tip of the manipulator acts as a grappling device for capture of payload-items and other systems with an EMI. Additionally, transfer of power and data once a system is docked to the end-effector is possible. This section describes the requirements of the end-effector, the mechanical design, the electrical components and finally shows the improvement of the current end-effector compared to the one of the predecessor project RIMRES.

System requirements

For anticipated mission scenarios the robotic systems need to interact with each other, e.g., to establish a logistics chain. In such a scenario, SherpaTT shall explore a planet's surface with the aid of Coyote III and PLIs which can be used to extend the capabilities of the implicated robotic systems in terms of autonomy, navigation or communication. The PLIs shall be transported to designated locations, deposited there for a certain amount of time and subsequently be recovered. The manipulation of the PLIs shall be performed with the end-effector on the manipulator arm mounted on SherpaTT. The resulting end-effector design requirements for the planetary rover SherpaTT are as follows:

- compatibility with the tip of the manipulator arm [6]
- ability to operate in planetary environments
- support for the mechanical, electrical and data interface of the manipulator
- usage of a (female part of) EMI
- provisioning of force torque data through a FTS
- covering shall be the mechanical supporting structure
- footprint of the end-effector shall not exceed the dimensions 150 mm x 150 mm (width x length) to be able to pick payload from designated payload bays
- support of visual servoing (without and with docked PLIs)
- ability to communicate with docked PLIs

In addition to the limited dimensions of width and length, the maximum allowed height for the end-effector is 75 mm. The height depends on the workspace of the manipulator arm, which shall be able to dock a stack of two docked PLIs into a payload bay of the rover's body. From the workspace limitation of the manipulator arm, a linear movement required for (dis)connecting from/to the body's EMI is possible with a

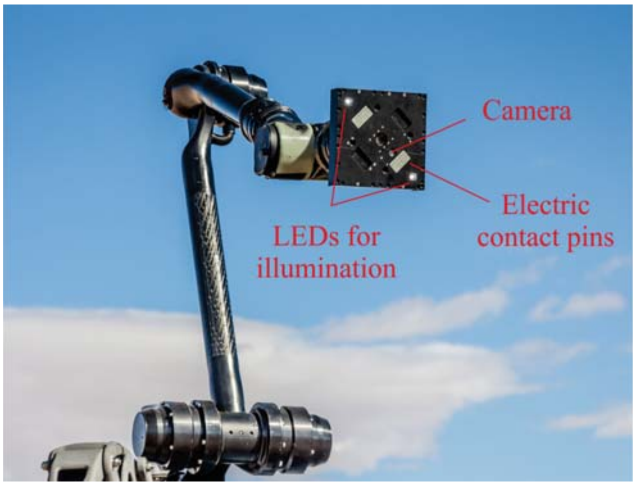


Figure 2. Bottom side of the end-effector

maximum linear distance of 375 mm perpendicular from the body's EMI surface. Since a stack of two PLIs has a height of 300 mm, the remaining height is 75 mm for the end-effector.

Mechanics

The key component of the end-effector is the female part of an EMI. The EMI ensures a reliable mechanical and electrical connection between linked robotic systems to allow for force, data and power transfer. The design of the interface focused on reusability, redundancy and robustness, e.g., the latch mechanism can handle a static load of up to 1300 N and undocking is feasible under a load of up to 300 N within different inclined positions [5].

To address the special needs of planetary space exploration the EMI remains operative in dusty environments. The EMI consists of a female and male part, which interlock using a latch mechanism after docking. Optical markers on the male part of the EMI and a camera on the female part allows for using visually guided docking approaches. During the docking procedure the guiding pins on the male part of the EMI and the conically shaped reception cylinders on the female part of the EMI enable docking in 4 different orientations (90° steps) and tolerate misalignment in the horizontal plane of up to +/- 5 mm displacement and up to $40°$ tilt angle and a rotational offset of up to 7°. Figure 2 shows the camera for the visually guided docking approach, the contact pins for electrical and data transfer after docking with other robotic systems and the LEDs for illumination during the docking procedure.

The covering of the end-effector is developed with a height of 75 mm and length and width of 150 mm x 150 mm. It consists of four detachable side panels, which also serve as supporting structure. The side panels interconnect the EMI with the 6 DOF FTS (Mini 45), Figure 4(a), the junction between the manipulator arm and the end-effector. A cooling fan, mounted inside of the end-effector ensures the cooling of the inner electronics. The removability of the side panels ensures easy access to the inner assembly space for maintenance. Figure 3 shows the current end-effector with one detached side panel.

Electronics

In addition to the above mentioned components, electronic parts like cables and a circuit board complete the end-effector.

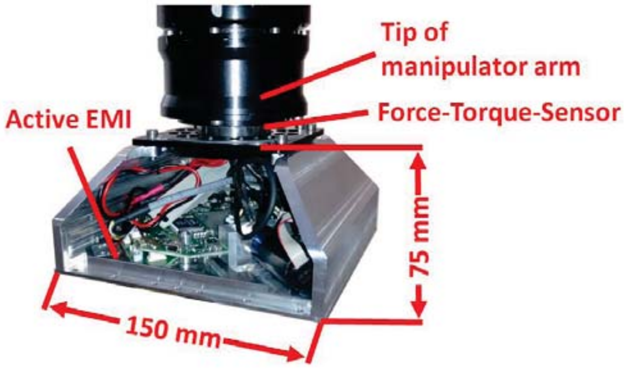
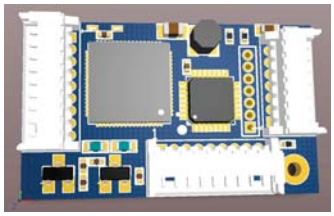


Figure 3. End-effector of SherpaTT

(a)FTS Mini 45 of the ATI company



(b)Circuit board of FTS

Figure 4. FTS and its circuit board

The cables for power and data transmission, which are needed to support the end-effector, are routed through the structure of the manipulator arm. These are in particular: (i) cable from the 48 V on-board electrical system of the rover, (ii) Low Voltage Differential Signaling (LVDS) cable for the FTS, (iii) RS-422 for the EMI, and (iv) Ethernet for the Gumstix . Inside the end-effector the cables are connected with the electronics boards of the EMI, as well as the circuit board of the FTS with dimensions of 30 mm x 18 mm (Figure 4(b)).

The circuit board includes a Programmable System-on-Chip (PSoc) microcontroller and an analog-to-digital converter (ADC) for reading out and pre-processing of the analog values of forces and torques. The data are sent via the Node-level Data Link Communication (NDLCom) protocol [20]. This protocol is designed for heterogeneous embedded communication networks and is used within all the robotic systems mentioned in this paper to connect different electronics. The circuit board allows voltages in the range from 5 of up to 8 V, thus a voltage transformer circuit board is used to down-convert the voltage from the 48 V power bus.

Since the electronics boards of the EMI dissipate heat, which leads to fluctuations of the FTS measurement values, a cooling fan with diameter of 40 mm is mounted inside of the end-effector to ensure the cooling of the circuit board.

Technical improvements in the current end-effector design

The structure of the predecessor end-effector consists of the female part of the first generation of EMI [21] on the bottom connected with four stiffeners on each side to the tip of the end-effector (cf. Figure 5) completed by an additional exterior covering. A brush, mounted on one side of the end-effector, allows to clean docking surfaces before docking.

With the development of the second generation of the end-

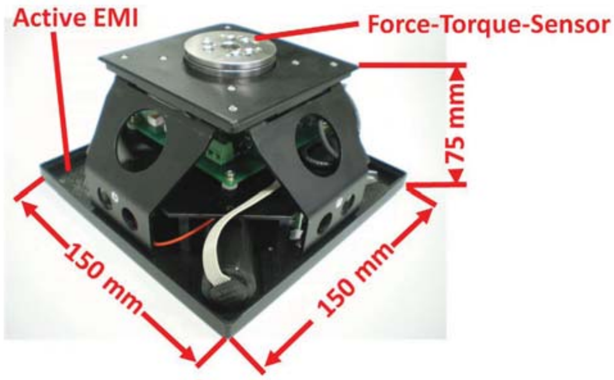


Figure 5. End-effector of Sherpa without the exterior covering

Figure 6. Extending of work ability by using of the sampling module docked on the end-effector

effector the following technical improvements were made:

1. improvement of the EMI [5]
2. easily detachable side panels
3. decreasing of covering parts
4. mounting of a cooling fan

Improvements of the EMI, which play an important role for the end-effector are (i) the positions of LED-lights for marker detection during the docking procedure, (ii) the improved visual positioning markers for a better detection in the camera image and (iii) a shorter central connection pin to allow a longer guidance period. This means the guiding pins lead the male EMI along the counter acting cylinders on female EMI for correct alignment, before docking the central connection pin during the whole docking process.

The detachable side panels of the current end-effector allow easy handling and quick access to the inner assembly space for maintenance and repair. Within the first end-effector the whole end-effector had to be removed from the tip of the manipulator arm in order to remove the overall coverage to reach the inner assembly space.

Since experiments showed that no brush on the end-effector is necessary to clean the docking surface before docking, the current end-effector has no brush. The field trials in the desert of Utah validated that docking surfaces were not covered by dust such that a cleaning is necessary. Nevertheless, a brush can be mounted once it is necessary.

4. End-effector handling

The end-effector is suited for a variety of manipulation tasks to support and extend the operational reach of the multi-robot exploration system. The main anticipated required operations are the exchange of PLIs between systems and the deployment of PLIs from and to the ground. The end-effector can grasp any PLI that is compatible with the EMI design, and even more, any (mobile and immobile) system equipped with an accessible male EMI can be grasped.

Generally, any connected PLI can also be used as a new kind of end-effector for grasping further PLIs, considering it provides a bottom male or female EMI. Therefore, there is no limitation on handling only a single PLI; multiple PLIs can be picked up at once or one after another. Clearly, this is only true as long as the bottommost attached PLI still provides a camera image to allow visual servoing.

A set of PLIs has been designed for evaluation purposes: (i) a battery module, (ii) a camera module, and (iii) a sampling module.

The design of this set of PLIs intends to enhance operation in the following ways: (a) extension of the power supply when the battery module is docked on the end-effector (or any other EMI of the system), (b) self-inspection of SherpaTT, or for observation purposes of the environment when the camera module is docked on the end-effector, and (c) soil sampling by using of the sampling module docked on the end-effector (cf. Figure 6).

Each designed PLI comprises a male EMI on top and a female EMI on bottom. The end-effector can attach to the male EMI of a PLI; using a mechanical lock mechanism guarantees a stable mechanical, electrical, and data connection between the end-effector and the attached PLI. The docked PLI can be used for further docking; relying on the female EMI at the bottom of the PLI. Hence, the end-effector is defined by the bottommost of the connected PLI.

During the field trials in Utah some typical reconfiguration operations were analyzed using a semi-autonomous control approach. For one evaluation scenario SherpaTT's end-effector is supposed to deploy a PLI onto Coyote III, Figure 7. The PLI is grasped by the end-effector in order to place it on Coyote III. With the bottom EMI of the docked PLI, the end-effector provides images for a visual servoing approach to perform the docking procedure. Once the PLI reaches the slot on the body of Coyote III, the mechanical, electrical, and data connections between Coyote III and the PLI are activated. Thereafter SherpaTT's end-effector can undock itself from the PLI.

The current end-effector on SherpaTT and the predecessor end-effector on Sherpa have been operated within different multi-robot systems. But since the manipulator arm is the same, both end-effectors can operate in almost the same range. This means, e.g., that not only the end-effector of Sherpa can carry the six-legged robot CREX [22] developed in the project RIMRES, see Figure 8, but also the current end-effector allows this operations.

Figure 7. PLI handling between Coyote III and the end-effector of SherpaTT

Figure 8. End-effector of Sherpa carries CREX

Visual Servoing

The end-effector described in this paper has been designed to satisfy the requirements for visual servoing of an attached manipulator. The inbuilt 5 mega-pixel camera can provide images with a resolution of up to 1024x768 px and at a frequency of approx. 1 Hz. For the visual servoing a resolution of 640x480 px is used.

The visual servoing approach is based on the following primary assumptions: (i) camera calibration has been performed, (ii) the payload for pickup resides in the workspace of the manipulator, (iii) the payload is further equipped with a compatible EMI, and (iv) the payload features two sets of visual markers in a predefined geometric arrangement.

As a prerequisite, the payload has to be reachable by the manipulator, but its exact position is unknown. For the visual servoing process to start, a set of markers has to be identifiable. In the case that the two assumptions do not hold, additional behaviour or high-level operation has to account for a search operation and possible relocation of the manipulator's mobile base, in order to make a visual servoing approach feasible at all. While a general visual inspection of a payload is possible to finally pickup a payload requires establishing the link between two compatible EMIs. The current design thus limits the general applicability of the end-effector to attach only directly to any payloads equipped with a male EMI. However, the application can be extended given specialized adapters are available. The general usage of the EMI in the visual servoing approach can be maintained as long as any attached payload or adapter provides a camera image for visual guidance.

The success of the visual servoing approach depends on a number of correlated factors: (i) quality of the camera calibration (ii) accuracy of the known camera position within the end-effector (iii) final accuracy of the marker detection

The general visual servoing approach consists of two main steps: (i) moving the manipulator to a known relative position with an offset only in z-direction at approx. 40 cm (ii) moving the manipulator to a known relative position with an offset only in z-direction at approx. 15 cm This two-staged approach is required to bring the end-effector first into a stable position for marker detection using a set of large (25 mm^2) markers which are detectable from greater distance, and the second approach brings the end-effector into a close range pose with greatest achievable accuracy by a set of small (9.8 mm^2) markers, in order to start the final approach. The final approach consists of a blind movement for a known offset. A fallback mechanism can be applied by interpreting force torque values provided by the end-effector, and comparing these values against a safety threshold.

Lighting conditions are a critical factor for the quality and success of marker detection. To improve marker detection and provide stable results in various environmental settings, all visual servoing operations take benefit of the end-effector's illumination capability.

The overall visual servoing process is using a very slow approach since the end-effector's camera provides images only at a very low rate. Figure 9 shows the control diagram of the visual servoing task.

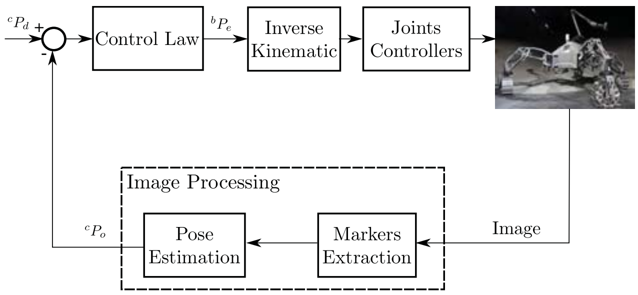


Figure 9. Block diagram

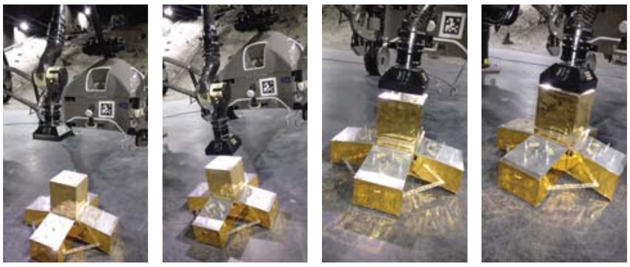
Docking procedure

The docking between two systems is a critical operation in a multi-robot scenario and relies on a visual servoing approach. The steps of the docking procedure is described and illustrated in the following. The docking procedure is divided into roughly four steps:

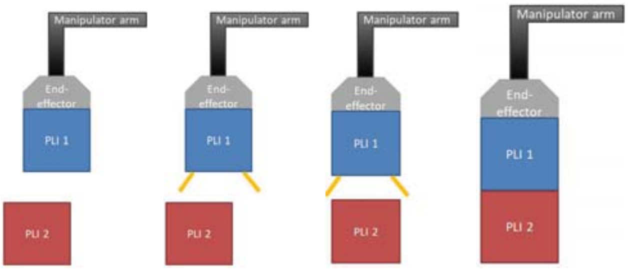
Figure 10(a) illustrates step one : moving of manipulator in the direction of the assumed position of the PLI.

Figure 10(b) illustrates step two: detection of the relative pose by finding the male EMI with its markers on the PLI, which is standing on, e.g., planetary surface, with the camera of the female EMI of the end-effector

Step 3, illustrated in Figure 10(c), consists of aligning both



(a)Step 1: moving to the assumed position of PLI (b)Step 2: Detection of the relative pose (c)Step 3: Aligning both EMIs (d)Step 4: Docking



(a)Step 1 (b)Step 2 (c)Step 3 (d)Step 4

Figure 10. Docking procedure using the end-effector to grasp a PLI

(a)End-effector of Sherpa

(b)End-effector of SherpaTT

Figure 11. Orientation of the female part of the end-effector EMI to the counterpart male EMI of e.g. a PLI

EMIs relatively to each other. Figure 11 shows the alignment of the female EMI attached on the end-effector on Sherpa and SherpaTT to the male part of the EMI mounted on one PLI. Depending on the set of markers used, step two and three can be repeated, as it is this case for final implementation.

The final step four is illustrated in Figure 10(d): locking the EMI on the end-effector with the latch mechanism. Thereafter, activation of the power bus and start of communication. By using the spring-loaded contact probes of the electrical contact it is possible to activate the power bus and start the communication before the docking procedure is finished.

The docking procedure described above use the end-effector and one PLI. As mentioned before, it is possible to perform the docking procedure once a PLI is docked on the end-effector (here: PLI1), as shown in Figure 10(a), 10(b), 10(c) and 10(d). The yellow lines on the end-effector in Step 2 and 3 (Figure 10(b) and 10(c)) present the light beams of the LEDs for illumination (Figure 2).

Figure 12. Setup on the end-effector for the repeatability test

5. EXPERIMENTS

This section describes the experiments performed with the end-effector in order to evaluate the requirements for any implemented docking approaches. One main influencing factor is the accuracy of the manipulator which is evaluated using two sets of experiments: The first set evaluates the pose accuracy with the manipulator arm fixed on ground in one experiment, and evaluates the pose accuracy while the manipulator arm is mounted on the robot SherpaTT in a second experiment. It was assumed that the pose accuracy of the manipulator arm fixed on ground is more accurate than the accuracy of the manipulator arm mounted on SherpaTT. The second set of experiments targets the characterization of any misaligment using force torque values. The result can be used to improve the safety of the docking approach and identify a nominal force torque value range.

Pose accuracy with a fixed manipulator

The pose accuracy of the manipulator arm is important in order to estimate forces and torques on the end-effector during docking operations with the manipulator arm. The end-effector itself can rely on the EMI to compensate for imprecise docking approaches, but to guarantee success the manipulator precision needs to be determined.

In the project RIMRES [2] a repeatability test had been implemented by DIN-standard DIN ISO 9283 [23]. This standard requires moving to five poses for 30 iterations. In between each run, joints were not re-initialized, because this impairs the values - measuring joint positions is based on optical encoders, but for re-initialising the ic-haus sensor is involved as an absolute encoder requiring a well-defined initialization position. Otherwise it can suffer from play in the measurement mechanism.

The test setup consisted of the manipulator arm, which was firmly fixed on the ground and the Vicon Motion Tracking System with a detectable target object mounted on the end-effector, Figure 12. The Vicon Motion Tracking System can measure positions with a precision of less than 0.1 mm.

The final measured precision for the position was 7.9 mm and $0.2°$. The result showed the general applicability of the manipulator with the end-effector to stack PLIs. However, the experimental procedure showed that the accuracy can be increased by additional tuning of the joint controllers.

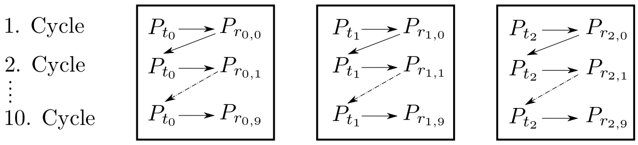


Figure 13. Experiment procedure for calculating the position repeatability

Position repeatability of SherpaTT Manipulator

Repeatability can be defined as the ability of the robot to reach a same desired pose for a repeated number of iterations under the same conditions. Repeatability of the manipulator depends on the resolution of the manipulator's joints and according to Mooring et al. [24]:

"Repeatability is a function of resolution, it is expected that repeatability will also vary throughout the workspace. Repeatability will be never be smaller than the resolution of the robot."

In following the procedures and experimental setup to identify the position repeatability of SherpaTT's manipulator is described: We used a motion tracking system *Qualisys* for tracking a marker which had been glued to the manipulator's end-effector. The tracking system consisted of six tracking cameras, which were placed around the manipulator. Each tracking camera was placed in such way that at least three cameras were able to see the tracking marker at any defined pose within the manipulator's workspace.

Figure 13 describes the experimental cycle in general: the end-effector is moved to a pose P_{t_e}, where e = 0,1,2 in the manipulator's workspace. This pose P_{t_e} is recorded using the motion tracking system, which provides the position of the tracking marker with respect to its reference frame. During each cycle the end-effector is moved from pose P_{t_e} to a random pose $P_{r_{e,c}}$, where $c = 1 \dots 10$. After reaching the random pose the manipulator is moved back to P_t. The now measured pose was saved, and the cycle repeated 10 times. The same experiment was performed for three different poses of P_{t_e}.

Figure 14 illustrates the results of this experiment set. In addition, the absolute position mean error (including all dimensions) for experiment 1 is: 3.29 ± 3.08 mm, for experiment 2: 2.77 ± 2.47 mm, and experiment 3: 1.86 ± 1.50 mm.

Experiments with Force Torques Sensor

The FTS mounted in between the manipulator's last link and the end-effector plays a significant role in avoiding any damages caused by the end-effector during the docking process. The following experiment is performed to estimate the force and torque exerted by the end-effector due to position error.

Within experimental setup the end-effector used on SherpaTT's manipulator arm operated with a PLI. The PLI is in initial position on the BaseCamp. When the end-effector reached the position as shown in Figure 15(a) the experiment started. In order to simulate the position error, the end-effector is deliberately moved while the PLI's four guiding pins are half inserted into the counerpart docking holes of the end-effector. In the first measurement series the end-effector moved 1 cm in positive and thereafter in negative X direction in order to measure the occuring forces and torques. During the ensuing measurement series the end-effector moved:

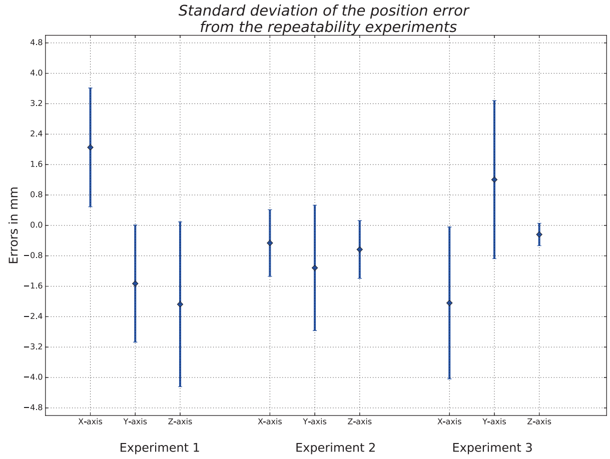


Figure 14. Standard deviation of the position error from the repeatability experiments

(a)End-effector partially attached to a PLI

(b)Close range view

Figure 15. Experimental setup for characterization of force torque values in case of misalignments

- 2 cm in positive and negative X direction
- 1 cm in positive and negative Y direction
- 2 cm in positive and negative Y direction

Figure 16 shows the force and torque measured by the FTS for a position error of 1 and 2 cm in positive and negative X direction. Figure 17 shows the force and torque measured by the FTS for a position error of 1 and 2 cm in positive and negative Y direction. As the experiments results show in figures 16 and 17, even for a position error of 2 cm the force and torque exerted by the end-effector on the PLI are high enough to break the guiding pins of the PLI. The measured values help to stop the docking procedure with a fallback if the forces or torques exceed a predefined threshold values.

6. Conclusion and Outlook

The presented end-effector of SherpaTT is able to dock different robotic systems under loads of up to 250 N, using autonomous visual servoing. Furthermore, the end-effector supports the setup of different mission scenarios. The experiments show that an application of the manipulator for blind docking approaches can suffer from the limited capability of moving to a particular position. These findings support the necessity for an application of visual servoing or other mechanisms which embed the external reference to a target docking object in order to compensate at least partially for these inaccuracies. The EMI incorporated in the end-effector compensates minor misalignments during the docking pro-

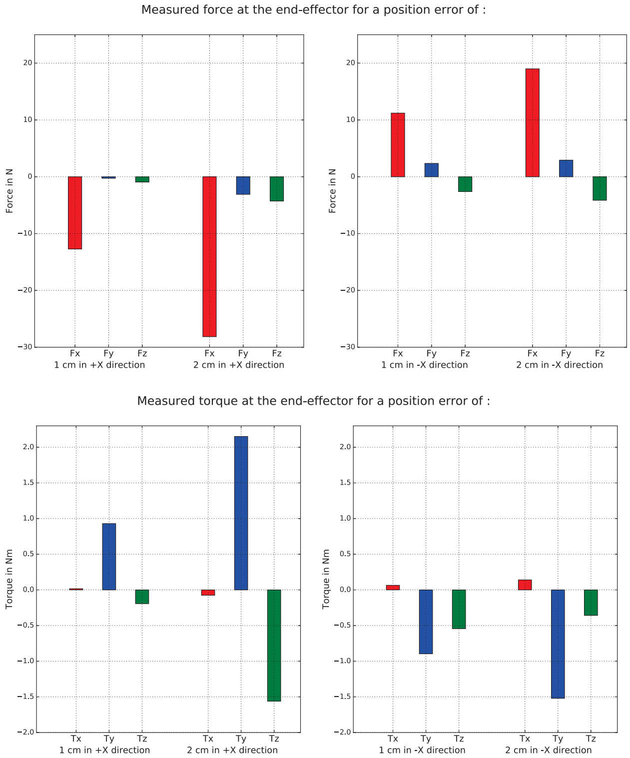


Figure 16. Measured force and torque at the end-effector for a position error in both positive and negative X direction

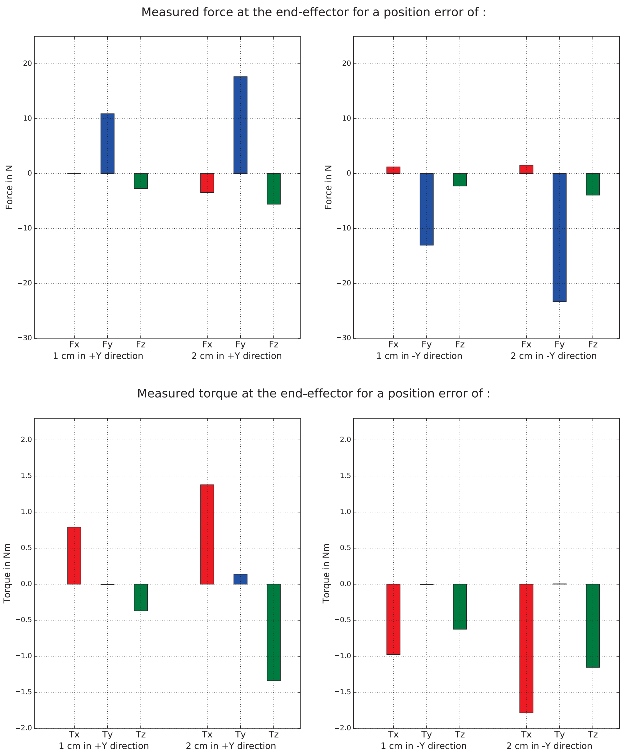


Figure 17. Measured force and torque at the end-effector for a position error in both positive and negative Y direction

cedure, but a mechanical misalignment system within the end-effector would help to increase the robustness of the docking approach. Using a force torque sensor for impedance or force control can further improve the docking process. These learned lessons will help to develop the end-effector in the H2020 EU-funded project SIROM (Standard Interface for Robotic Manipulation of Payloads in Future Space Missions), which will deployed at the manipulator arm of SherpaTT for experimental verifications for future planetary missions [25]. Furthermore, an extension of functionality by employing thermal transfer into the EMI is necessary for increasing the space application readiness of a general electro-mechanical interface/end-effector. A thermal transfer type will be inserted into the SIROM interface and thus within the prospective end-effector by SIROM.

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