Robotic Technologies for In-Space Assembly Operations

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***Abstract*— On-orbit robotic assembly is a key technology that can increase the size and reduce costs of construction of large structures in space. This document provides an overview of existing or emerging robotic technologies for space-born assembly, including also the development of standard interfaces for connectivity that combine mechanical connections with electronic and power signals. Technologies that can enable on-orbit assembly demonstrations in the near future are currently under development at the Institute of Robotics and Mechatronics in the German Aerospace Center - DLR, as showcased in a setup for autonomous assembly of structures made out of standard aluminium profiles.**

I. Introduction

Large scale space mission scenarios for the Post-ISS era, e.g., Moon Village (ESA), Mars exploration (NASA), and Orbital HUB in LEO (DLR) [1], require the availability of dexterous robot systems capable of performing complex assembly tasks. In contrast to the construction of ISS, which was performed by astronauts and took over a decade, it is intended for new missions to be assembled by robotic systems. In the last two decades, robotized On-Orbit Servicing (OOS) missions are increasingly gaining importance. OOS addresses the maintenance of space systems in orbit, including repairing and refueling, using technologies that can be extended to the construction of large space structures.

On-orbit robot assembly could allow the construction of much larger orbital structures, for instance for setting up more sensitive radar imaging or for obtaining much higher speed of communications by assembling bigger and more sensitive antennas. Current manufacturing and technological limitations are reached in the construction of antennas and mirrors when they have to be deployed from a single launch with a single satellite. However, a dexterous and capable space robot could assemble pieces from multiple launches in space to construct antennas and other structures of enormous size, thanks partially to the expected reduction of launch costs due to the recent success of private launch providers such as SpaceX and Blue Origin.

In the future, robotic construction capabilities could also be applied to create space infrastructure, standing structures such as refueling depots, in-space manufacturing facilities, space-tourism complexes, and asteroid mining stations [2]. It is expected that within five years we can have systems in orbit able to demonstrate the autonomy, dexterity, and delicacy needed to work on these far-reaching capabilities. These developments will allow the enhancement of functionalities in current missions such as DARPAs RSGS and NASAs Restore-L well beyond servicing existing satellites.

Autonomous robotics has become a feasible alternative for servicing and maintenance missions. While operations such as autonomous rendezvous, docking and undocking are relatively common nowadays, autonomous on-orbit robotic servicing is currently under development [3]. Some concepts for robotic on-orbit assembly are being developed, and they are mostly at conceptual level [4]. This work provides an overview of such technologies aiming to create autonomous assembly capabilities (Section II).

Main in-space assembly technologies used so far by astronauts for applications such as the construction of the ISS or the reparation of the Hubble telescope include the deployment of truss and beam sub-assemblies, with revolute joints or special latches for easy snap-on, and in-space manufacturing using additive manufacturing techniques [5]. Independently of the technology used for the mechanical frame, one of the main challenges for assembling a large functional structure is the combination of power and data connectors together with the mechanical latch. Possible alternatives for solving this issue include magnetic latching and reversible joints that allow disassembly for repairing or for module replacement. A brief overview of standard interfaces that allow full functionality for modular assemblies is presented in this work.

Robot-based assembly in the absence of gravity addresses fundamental technical questions that do not exist for terrestrial applications. The robot is mounted on an actively regulated platform (either a simple satellite or a large assembly platform), and the motion of the robot has dynamic effects on the platform itself. The dynamic effects depend on the mass of the objects and the velocity of the motion. When the robot works on a platform different to its own floating base, the required physical contact affects both platforms. The contact can also affect the perception system, as minor changes in position might lead to significant visual occlusions. These effects must be considered on the motion planning for the robotic manipulator.

While teleoperated or partially assisted assembly operations are possible on ground, autonomous assembly of structures has been recently proven feasible through the combination of adaptable perception, integrated assembly and grasp planning, and compliant control of the manipulators [6]. A description of such ground-based demonstrator is presented in this work (Sec. III). The paper concludes with a discussion on the open topics in the field of autonomous on-orbit robotic assembly.

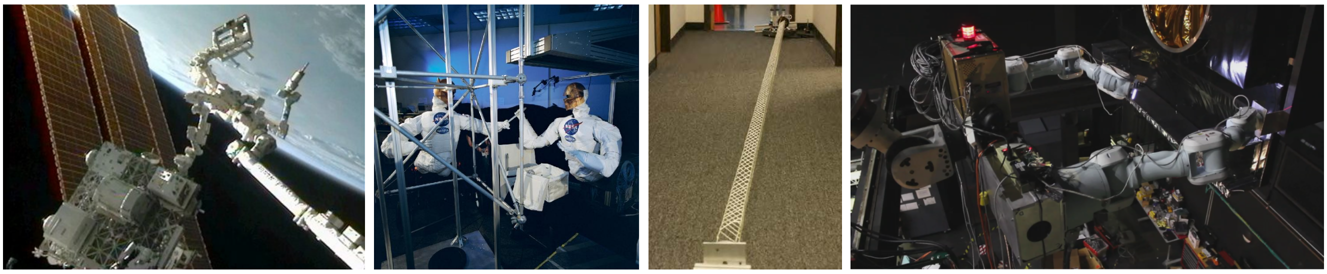

Fig. 1. Current robotic demonstrations of in-space assembly. From left to right: Dextre approaching the RRM module (Courtesy of NASA), Robonaut assembling truss structures on ground (Courtesy of NASA), Trusselator for SpiderFab (Courtesy of Tethers Unlimited), and initial ground demonstration of Phoenix (Courtesy of DARPA).

II. Overview of existing in-space robotic assembly technologies

In-space assembly has been studied for more than 3 decades now [7] due to the great potential applications for performing tasks such as assembling systems larger that current cargo areas in commercial transportation vehicles, and can also be applied to more commercially interesting activities such as repair, refuel and upgrade of current satellites. Possible applications of in-space assembly include asteroid redirect vehicle, artificial gravity vehicles, space transportation hub, space telescopes, in-situ resource utilization for construction, solar electric power and propulsion, sun shields, atmospheric deccelerators [5]. An analysis of the potential applications shows that the demanded cross-cutting (non application-dependent) capabilities are robotic assembly, standardized interfaces, modular design with high stiffness, deployable subsystems, and docking and berthing. This survey is focused on the topics of robotic assembly and standardized interfaces, which are more relevant for roboticists working for space applications. The design of deployable structures with high stiffness corresponds to the subfield of space architecture, and autonomous docking and berthing are maneuvers that have been tested in multiple occasions and are currently under development for on-orbit servicing operations [3].

A. Technologies for robotic assembly

Several on-orbit servicing missions have been carried out, and are creating the technological basis for on-orbit assembly. The first robotic on-orbit servicing mission was performed by NASDA (now JAXA, Japan) with the ETS-VII (KIKU-7) mission [8], [9]. It used the first satellite equipped with a robotic arm, a 6 DoF, 2 m long manipulator, which was employed mainly to perform experiments of rendezvous docking between a chaser (Hikoboshi, with 2.5 ton) and a target (Orihime, with 0.4 ton), and also to prove the feasibility of doing an ORU (Orbital Replacement Unit) exchange. Experiments were performed in 1999 [10]. In 2007, experiments of the mission Orbital Express [11], [12] took place. This mission was a joint effort of DARPA and Boeing, and demonstrated rendezvous, docking, fluid transfer and ORU transfer between two satellites, a servicing satellite equipped with a 6 DoF arm, ASTRO, and a serviceable satellite, NEXTSat [13].

Different technologies have been proposed for robotic assembly in space, although real experiments have been performed only to the level of servicing and maintenance tasks, mainly with the Dextre manipulator (Fig. 1). Dextre, also known as the Special Purpose Dexterous Manipulator (SPDM), was assembled in 2008 onboard the ISS. It was built by MacDonald, Dettwiler and Associates (MDA) and maintained by the Canadian Space Agency (CSA). The original goal of the robot was to relieve astronauts from external servicing and maintenance tasks on the ISS, including removal and installation of batteries, opening and closing covers, or reconnecting cables [14]. It has also been recently used for removing cargo payload from supply ships like the Dragon capsules. Dextre is a dual arm manipulator, each arm with 7 joints and a length of 3.35 m, and a total mass of 1560 kg [15]. It has a power fixture at the "wrist", which can be grasped by the Canadarm for repositioning at different work sites, or can also be attached directly to the ISS. For performing operations, Dextre moves one arm at a time, teleoperated either from the ISS or from a ground control center. In 2009 NASA initiated the Robotic Refueling Mission (RRM), aiming to use Dextre for performing robotic servicing tasks in orbit, including refueling and maintenance [16]. The first phase was developed between 2012 and 2013, and employed four different tools: a wire cutter, a multi-function tool, a safety cap removal tool, and a EVR nozzle tool. It proved that the robot was capable of performing on orbit refueling of existing satellites. The second phase was launched in 2013 to further mimic servicing tasks, which were performed between 2015 and 2016. The tasks included the installation of two task boards onto an existing module, the visual inspection of Canadarm using a specialized tool, and assessment of performance of a solar cell. The mission ended in March 2017, with the removal of the RRM payload.

Since 2011, Robonaut 2 (Fig. 1) became the first humanoid robot in Space [17]. It was co-developed by NASA and General Motors (GM) to serve as an assistant to human workers [18]. The initial Robonaut included only the torso, but in 2014 the mobility platform for Robonaut was delivered, to augment the robot with two legs for maneuvering inside the ISS. The robot has human-like arms and hands, which enables it to use the same tools as the crew members. On-ground tests have demonstrated the ability of

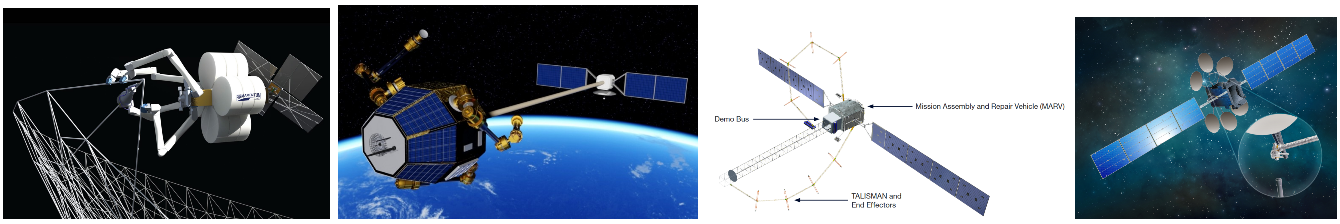

Fig. 2. Different robotic concepts for in-space assembly. From left to right: SpiderFab (Courtesy of Tethers Unlimited), Archinaut (Courtesy of Made in Space), CIRAS (Courtesy of Orbital ATK), and Dragonfly (Courtesy of Space Systems Loral).

Robonaut to perform different tasks, including assembly of truss structures [19]. On-orbit uses of Robonaut so far have been limited to cleaning and monitoring tasks inside the ISS, although the robot has the potential for becoming a useful assistant for instance in EVA tasks.

Traditionally, satellites are fabricated and tested on ground, and then launched as payload on rockets. This demands a large effort and cost in the preparation of the system to survive the launch process, while the size of the satellite is limited by the cargo capabilities of current spacecrafts. To survive these restrictions, Tethers Unlimited has proposed the SpiderFab architecture [20], a satellite "chriysalis", combining manufacturing techniques with robotic assembly technologies (Fig. 2). This effort was supported through a NASA Innovative Advanced Concepts (NIAC) grant [4]. The architectural concept includes:

- Techniques for processing suitable materials to create structures: while most rapid prototyping techniques on ground rely on gravity to facilitate bonding of the materials, the microgravity environment in space calls for a different approach. However, the lack of gravity also means that structures can be fabricated in any direction without distortions introduced by gravity. The system proposes the combined use of Fused Filament Fabrication, with automated fiber layup, such that the system can 3D print high-performance reinforced polymers. An initial test of the manufacturing of supporting structures was performed with the "Trusselator" ((Fig. 1)), for creating large truss structures by using a continuous fiber reinforced thermoplastic yarn [21]. This technology was recently selected for a new project, the MakerSat, aiming to endow small satellites with structures that allow them to achieve the performance of larger satellites.
- Mechanisms for mobility and manipulation of tools and materials: involves the use of multiple dexterous robot arms to position the fabrication heads, position the robot along the constructed structure, and position the structural elements for assembly. As initial concept, the "Kraken" 7 DOF, 1 m long arm was developed for nanosatellite applications, and delivered on Feb 2013.
- Methods for assembly and joining structures: bonding can be accomplished in multiple ways, including welding, mechanical fasteners, adhesives, and snap-on latches. Fusion bonding can also be exploited by combining heat and pressure to fuse thermoplastic materials.
- Thermal control: one big challenge is the control of temperatures and heat gradients on the manufactured parts, especially considering the influence of the sun and the position on orbit. The materials must be processed such that they cool and solidify in a manner that does not induce undesired stresses in the structure.
- Metrology to enable closed-loop fabrication: required to measure the overall shape of the structure, and to enable accurate positioning of the fabrication heads.
- Methods for integrating functional structures: the concept of SpiderFab is focused on creating support structures, but it requires also suitable mechanisms to integrate functional elements that will be produced on ground, such as solar cells, antenna panels, sensors, wiring, reflective membranes, and payload packages.

In 2012 DARPA started the Phoenix program, aiming to demonstrate the capabilities of a multi-arm satellite with tool changing capabilities (Fig. 1). The final goal is the creation of a geoestationary satellite capable of servicing an operational spacecraft by 2020 [22]. The short term mission goals are repairing of satellites, such as fixing a component or deploy an antenna. Medium term goals include performing upgrades on orbit, and the long term goal is the construction of satellite hardware on orbit. The arms for the satellite were developed under the FREND program (Front-End Robotics Enabling Near-Term Demonstration); they have 7 DoF, a weight of 78 kg, and a total length of 2.5 m [23]. The arms were designed for grappling and repositioning Resident Space Objects (RSOs). As part of the Phoenix program, the arms are upgraded, new components like tools and tool changer are to be designed, and novel algorithms for control, teleoperation, mission sequencing and fault detection are also expected. A video with some of the on-ground results of the project can be found in [24]. A similar mission currently under development is Restore-L, aiming to create a spacecraft with the tools and technologies required to extend satellites' lifespans [25].

At the end of 2015, NASA announced new Public-Private Partnerships to advance "Tipping Point", Emerging Space Capabilities. Three projects were selected to explore the future of robotic in-space manufacturing through manipulation of structural trusses: Archinaut, CIRAS and Dragonfly (Fig. 2). Phases A/B will be developed during 2 years, before entering the potential flight demonstration phase in 2019.

The first project, Archinaut (officially called Versatile In-Space Robotic Precision Manufacturing and Assembly

System) is under development by Made In Space Inc. It aims to construct, assemble and integrate larges structures in space [26]. It is constructed around a space-capable manufacturing unit based on an Additive Manufacturing Facility, already tested on the ISS, and capable of producing structures larger than itself. The setup for testing additive manufacturing of structures is called ESAMM (Extended Structure Additive Manufacturing Machine), and is intended to test manufacturing in a simulated space (thermal-vacuum). To provide the assembly robotic component, the 3D printer will be complemented with three manipulator arms built by Oceaneering Space Systems, which help to conform the "Ulisses" spacecraft for in space manufacturing. Northrop Grumman will provide systems engineering, control electronics, software, testing and assistance with Archinauts space station interface.

The second project is called CIRAS (Commercial Infrastructure for Robotic Assembly and Services), and is carried out by Orbital ATK [27]. It aims to attach and detach a solar array, demonstrating assembly and reuse capabilities on an integrated ground test using an air-bearing laboratory. The system will use two upgraded 15-meter TALISMAN (Tension Actuated Long Reach In-Space Manipulator) together with precision EBEAM welding using reversible quick-connects, and a special jigging precision assembly robot. The project builds upon existing capabilities of the Lightweight Surface Manipulator System (LSMS) [28].

The third project is called Dragonfly, or On-Orbit Robotic Installation and Reconfiguration of Large Solid RF Reflectors [29]. It is developed by Space Systems Loral. The project aims to modify existing antenna and robotic equipment to perform a flight demonstration of antenna assembly for a GEO satellite. It intends to use existing assembly interfaces with robot manipulators, and demonstrate stowage techniques for larger than traditional solid reflectors for a potential launch. Tethers Unlimited is a partner in this project, contributing with the in-space truss manufacturing facility developed with SpiderFab.

Concepts for an on-orbit servicing mission that can be potentially expanded for on-orbit fabrication have also been developed at DLR, with the DEOS (Deutsche Orbitale Servicing Mission) [30]. As part of the preparation for these activities, DLR developed the OOS-SIM, an On-Orbit Servicing simulator (Fig. 3).

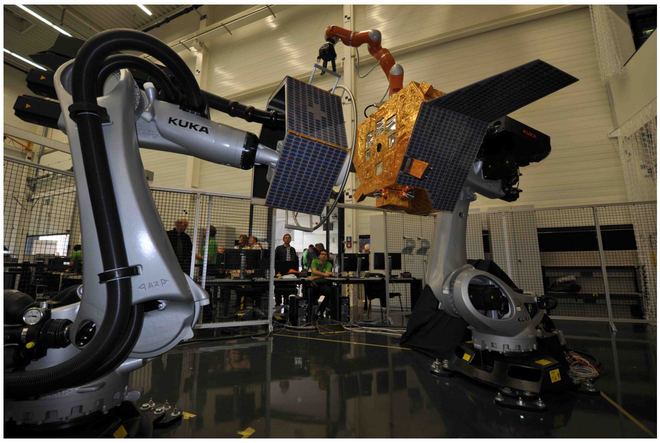

Fig. 3. OOS-SIM, an on-orbit servicing simulator developed at DLR.

Fig. 4. Existing standard interfaces: Top left: EE on SRMS (Courtesy of NASA), Top right: LEE on SSRMS (Courtesy of NASA), Bottom left: JEM EE (Courtesy of JAXA), Bottom right: OTCM (Courtesy of NASA).

B. Connectivity and interfaces

A standard interface is defined as a combination of devices that allow to couple active payload modules (APMs) to a manipulator, amongst themselves, and to spacecraft. It shall allow transferring of mechanical loads, electrical signals and data, as well as thermal flux between the coupled modules. [31]. A recent review on standard interfaces can be found in [32]. This section focuses mainly on detachable interfaces for orbital robotics. Several interfaces have already been implemented for space missions (Fig. 4). The robotic arms often possess an End Effector (EE) that interfaces with a grapple fixture. Examples are the Shuttle Remote Manipulator System (SRMS), and the latching end effector (LEE) equipped on the Space Station Remote Manipulator System (SSRMS). The JEMRMS (Japanese Experiment Module Remote Manipulator System) of ISS Japanese experimental module (JEM), has a similar mechanism to interface with several kinds of common grapple fixtures placed on various components of ISS modules. Their ability to grasp and move massive objects in space environment has been significantly demonstrated so far in different ISS projects. Also, the ORU/Tool Changeout Mechanism (OTCM) of the SPDM can select several tools to attach on its tip so as to conduct various works. A typical interface such as LEE is a detachable electro-mechanical interface (DEMI) designed to possess gender, i.e. an EE side and a grapple fixture side. All the interfaces possess active mechanisms on the arm side, an exclusive actuator used only for the docking operation.

Besides those practically implemented interfaces, there are several interfaces developed on ground aiming for future implementation. As part of space-borne manipulator, JAXA has developed an EE (JAXA EE, Fig. 5) and grapple fixtures aiming to be used for construction of large space structures.

Fig. 5. Different standard interfaces: Top left: JAXA EE (Courtesy of JAXA), Top right: CTED (Courtesy of ESA), Bottom: RSGS interface (Courtesy of MDA).

However, the majority of interfaces in space are designed to be used mainly as pure electro-mechanical connections between components. A typical example is the Compact Tool Exchange Device (CTED, Fig. 5), developed for connecting DexArm (ESA) and Dexhand (DLR) [33]; it was initially developed as part of the EUROBOT project. The RSGS interface (RSGS IF, Fig. 5) was developed by MDA and adopted to interface between the FREND arm and different EEs. Also MDA has developed a passive interface mechanism (MDA PIF, Fig. 6) for the Next Generation Canadarm (NGC) project of CSA, to interface mechanically between the NGC arm and tool tip. Another interface named DWIM (Fig. 6) was developed by Tokyo Tech, as an interface for a manipulator of an astronaut supporting robot. While DWIM and MDA interface are detachable mechanical interfaces (DMI), the other 3 (JAXA EE, CTED, RSGS) are DEMI. Also, all interfaces possess gender. In addition, all of them are active, except for the MDA passive interface (has no actuator on both sides).

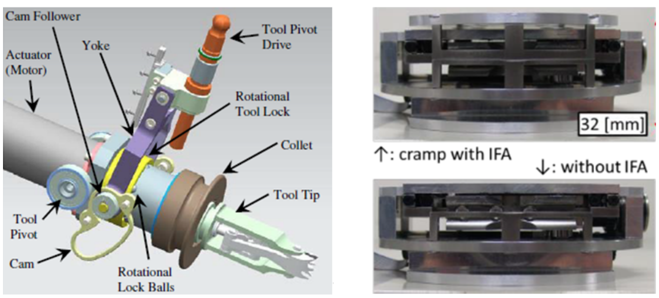

Fig. 6. Different standard interfaces: Left: MDA Passive IF (Courtesy of MDA), Right: DWIM (Courtesy of Tokyo Tech).

For comparison, standard industrial manipulators use industrial adapters like the SWS series from Schunk for changing tools (Fig. 7). It is an electro-mechanical interface that goes from 40 mm to several hundred mm in diameter. For basic information as an interface, the SWS-060 Schunk adapter is a DEMI, and it possesses gender to be able to use an active mechanism on the arm side that adopts pneumatic actuation to dock/undock the tool [34].

Fig. 7. Standard industrial adapter: Schunk SWS-060 (Courtesy of Schunk).

III. Autonomous Robotic Assembly

Common robotic systems in space applications have a small degree of autonomy. The execution of tasks usually relies on teleoperation, which requires an appropriate feedback channel for the operator, typically affected by substantial time delays. The concept of shared autonomy increases the dexterity of such systems and reduces the effort for the operators in complex tasks [35]. Nevertheless, teleoperation approaches only have limited use when it comes to the assembly of complex structures. Because of the fine granularity of assembly tasks, classical teleoperation becomes unfeasible as it consumes substantial amounts of time for the synchronization of operator commands and manipulator actions. Therefore, a robotic assembly system should be capable of performing a sequence of operations or even the complete assembly task autonomously.

A. *Robotic Assembly System*

A prototypical system for autonomous assembly of aluminum structures was recently developed at DLR [6]. It was developed for a terrestrial use case, however, it demonstrates the potential of such systems in space applications. The structures are made up of a modular building kit system typically used in industrial facilities for the setup of production equipment, composed by aluminum profiles of various lengths and angle bracket connectors. The system automatically decomposes a given assembly specification, i.e. a list of parts and their relative configuration, into a task sequence, which is then mapped to a sequence of appropriate robotic skills. Fig. 8 shows the workflow starting with an assembly planning unit, followed by the task to skill mapping and finally by the skill execution.

Although the first humanoid robot is already in space operation [17], the general dexterity and sensing capabilites

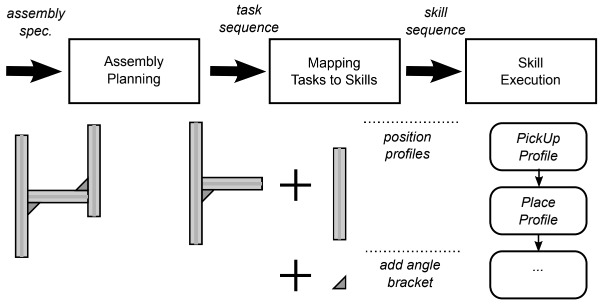

Fig. 8. Workflow of the robotic assembly system. An assembly specification is automatically decomposed into a task sequence and then mapped to appropriate robotic skills.

for the autonomous execution of complex assembly tasks are not yet reached. For our system, we combine general dexterous manipulators with specialized tools and grippers suitable for the target building kit. The initial demonstration of autonomous assembly was performed with a single arm and a number of specific assembly fixturing units conveniently located in the robot work cell. The setup was recently extended with a second robot arm (Fig. 9), to completely remove the required fixtures, thus increasing the flexibility of the system and enabling the assembly of more complex structures thanks to the implementation of multi-arm collaboration and manipulation. The system consists now of two KUKA LBR iiwa R800 manipulators, each arm with 7 DoF and equipped with joint torque sensors. The manipulators are the industrial version of the light-weight robot arm (LWR) technology developed at DLR-RM [36]. The robotic components of the LBR were verified for space applications in the ROKVISS mission with experiments on the ISS [37]. The sensitivity and the impedance control mode allow robust and stable fine manipulation especially in contacts, which is essential in the autonomous execution of assembly tasks.

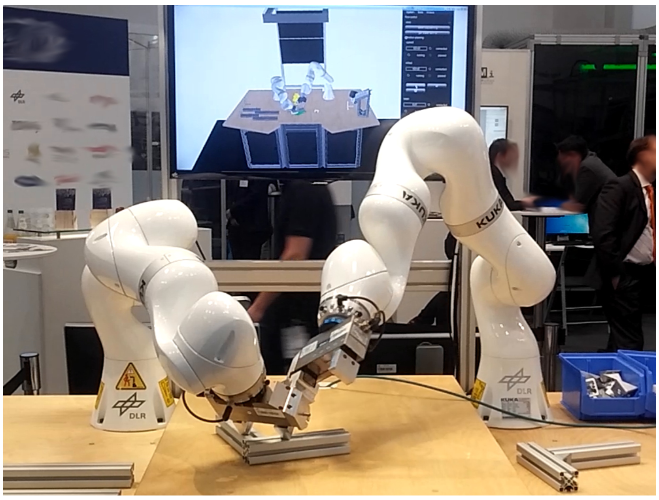

Fig. 9. Two light-weight robot arms (KUKA LBR iiwa) collaborate in the assembly of aluminum structures.

Fig. 10 shows the selected end effector, an industrial Schunk WSG 50 gripper, with its specific finger design for the parts and tools of the building kit. The modified geometry of the fingers allow form-closure grasps for the parts and the required tools (screwdriver). In this way, grasping uncertainties are reduced significantly and grasp stability can be guaranteed directly by the mechanical design. The two actuated fingers are mainly used for power grasps, while an additional third finger is designed for grasping angle brackets and slot nuts, and features a small pin for the positioning of slot nuts inside the profiles.

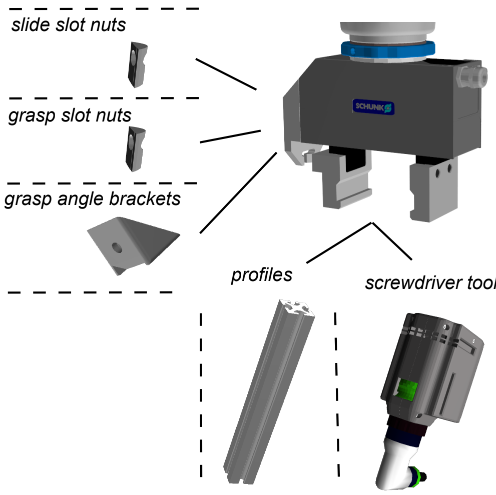

Fig. 10. Adapted mechanical gripper (Schunk WSG 50), designed to support a high number of stable grasps and actions for the given building kit.

B. *Robust Assembly Skills*

Modularity is an important requirement for building sets for larger structures. An infinite number of structures can be constructed with the building set used in this demonstrator. The square-shaped profiles are customizable in length, and connections can be freely placed along the four sides. A single connection between two profiles is made with an angle bracket, which is fastened with screws and nuts in the slots of the profiles. The subtasks that the system must combine during the construction of a given assembly are [6]:

- insert slot nuts in the profiles
- position profiles
- add angle bracket
- add screws

All subtasks require robust assembly strategies. These strategies are implemented in basic skills that encapsulate the robot capabilities in a parametrizable and reusable way. Skills can be adapted to the current task and through a certification process the desired behavior can be guaranteed for solving a given task, as shown in the RACElab project for human-robot collaboration. Fig. 12 shows an example of sequence of actions for the slot nut insertion. Open-loop robustness on a higher level is achieved here thanks to the sensitivity of the robot arm and the impedance controller. A robust strategy for such insertion tasks can be chosen considering the passive alignment properties and the compliance of the robot in the contact [38]. Furthermore, observation algorithms based on the joint torque measurements are currently developed to reduce uncertainties and monitor the execution [39].

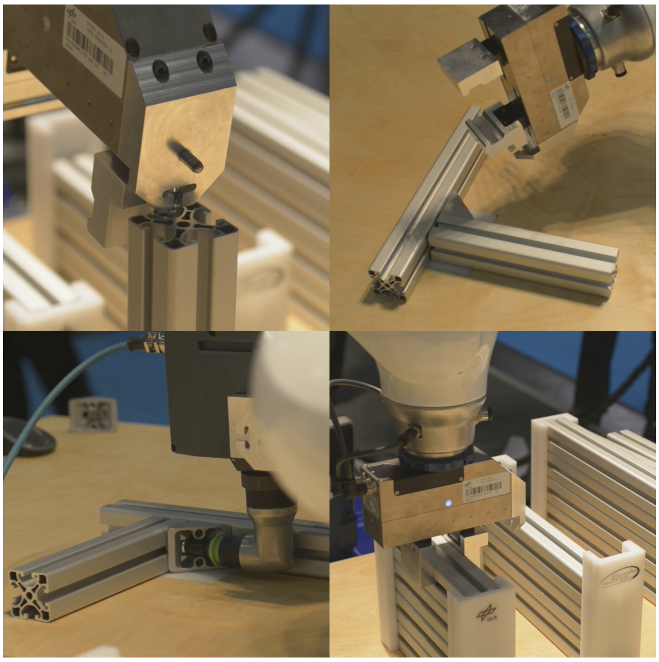

Fig. 11. Realization of various subtasks. Slot nut insertion, placement of an angle bracket, pickup of a profile from the parts depot and fastening of the angle bracket with the screws with the help of the screwdriver (clockwise).

C. Planning for Autonomous Execution

For complex and large structures it might not be possible to engineer and precompute every assembly step in detail as the system might need to adapt the execution according to the present state of the environment. In order to achieve the required autonomy, our system uses a set of dedicated planners located in the planning unit. The main objective is to select and parametrize the skills for the present tasks. Threrefore, an assembly sequence planning, a grasp planning and a motion planning component are tightly connected through a runtime world model for symbol grounding according to the present state of the assembly, as depicted in Fig. 13. The sequence planning considers geometrical constraints in an assembly-by-disassembly approach to find a feasible sequence of tasks. Grasps are generated and checked for feasability for all subassemblies [40]. The selected skills access the data from the planners in order to find the appropriate configurations, e.g. a specific grasp is selected amongst the available grasps in the database, according to reachability criterions and available paths provided by the motion planner [6]. The motion planner therefore synchronizes its internal geometrical representation with the runtime world model in which all objects are registered with type and pose, and are also labeled semantically to connect with the planning units and skills. So far, the system is capable of planning automatically sequences for planar aluminum structures by only providing a specification of the desired assembly goal. In future work, we plan to add more flexibility to the system by using advanced reasoning algorithms and more complex structures based on an expanded set of connectors.

IV. Final discussion

New technologies like additive manufacturing of components have been recently introduced for space applications by companies such as Made in Space. However, the construction of large scale structures nowadays and in the short term will still rely on robotic manipulators for performing delicate on-orbit assembly operations. Several challenges remain to proof the feasibility of this ambitious idea, but initial tests on ground have tested the capabilities and versatility of autonomous assembly using robotic manipulators. These terrestrial applications typically rely on the use of fixtures that provide mechanical support during the assembly operation. However, the use of fixtures in space can be limited due to the dynamic effects of zero gravity conditions. Feeding of parts for the assembly, size of the parts to be handled, feasibility and limits of usage of one or two arms for the operations, or use of assembly kits are still open questions in the field. The extension and testing on relevant environments of zero-gravity autonomous robotic assembly is a current topic of interest at DLR.

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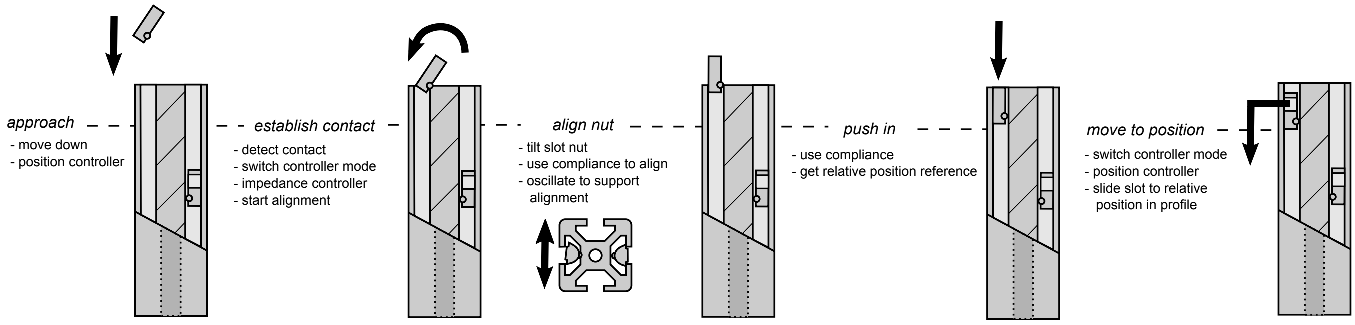

Fig. 12. Implementation of open-loop robustness in the insertion of the slot nut in a profile. The actions use the sensitivity of the robot arm to detect contacts and the compliance of the impedance controlled arm for the compensation of position uncertainties.

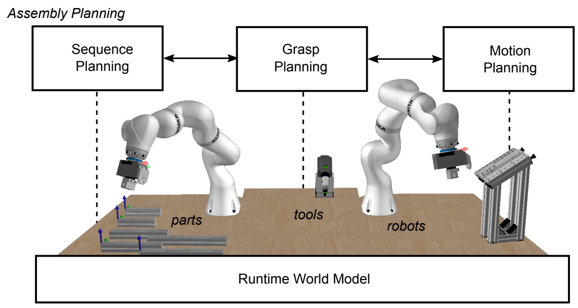

Fig. 13. Components of the planning unit for the autonomous execution of assembly skills. The sequence planner, the grasp planner and the motion planner interact with a runtime world model to select and parameterize an appropriate sequence of skills.

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