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ABSTRACT

This paper provides the programmatic context in which the European Space Agency (ESA) is and hence serves as orientation background, introduction and index to the several papers on ESA missions and ESA-sponsored technologies submitted to i-SAIRAS 2020.

ESA, on behalf of the European Union, leads a team of European space agencies that coordinate the H2020 Strategic Research Cluster (SRC) in Space Robotics developments under European Union funds. The paper also illustrates goals and steps of these developments and provides the context for the SRC papers submitted to i-SAIRAS.

To substantiates the continual aspects of some technologies, the paper also recalls earlier developments which present ones continue/improve upon.

1 ORBITAL ROBOTICS

1.1 On-Orbit Servicing, Refueling, Assembly, Manufacturing (OOS), demonstrators

Since the termination at PDR of both the DEOS (DLR) and CAPTARE (DLR and ESA) missions, activities in this field have re-started from scratch.

At ESA a call for the provision of a service aiming at de-orbiting an ESA-own debris and also demonstrating on-orbit servicing was issued in summer 2018. Out of the initial set of outline proposals received, ESA encouraged 6 proposers to provide detailed proposals. Out of the second round of evaluation, the proposal from the CLEARSPACE consortium was accepted and negotiated. The mission, called CLEARSPACE-1 by the consortium and ADRIOS by ESA, will however target only de-orbiting i.e. Active Debris Removal.

The European Commission, within the H2020 Strategic Research Cluster (SRC) in Space Robotics Technologies has issued in October 2019 a call for awarding 2 operational grants (OGs) to study, up to phase B1a demonstrator of OOS based on the technologies developed in the SRC . Proposals were due at the time of the COVID-19 outbreak.

The demonstrators are requested to advance the concepts of modular spacecrafts as assumed in the H2020 OG5 (SIROM project), OG8 (PULSAR project) and OG9 (MOSAR project) and also promoted initially by the DLR project "intelligent Building Blocks for On-Orbit Satellite Servicing and Assembly " iBOSS.

Outside Europe, there has been a surge of activities in satellite servicing, which also have the influence of European actors.

The most notable one is Northrop Grumman's MEV-1 satellite servicer, launched in 2019. Northrop Grumman has been contracted by Intelsat for a second satellite servicing mission (MEV-2) to extend the life of the Intelsat-1002 satellite.

It should be noted that the MEV spacecraft use critical European technology (StarTracker, RVD Cameras and LIDAR all from Jena Optronik) .

1.2 Active Debris Removal

Independent studies on the risk posed by orbital debris to space infrastructure have shown that the population of debris in LEO will likely keep increasing, even when mitigation efforts are universally adopted.

Therefore active removal of debris must be performed in order to avoid the Kessler syndrome with a rate that is estimated to be from 5 to 10 large objects that need to be removed from orbit per year.

Despite the scientific evidence, standing now for at least 5 years, no solution to this problem has been activated.

At ESA the proposal to implement a demonstration mission that would de-orbit the Envisat defunct satellite, failed to get member states support, due to stated excessive cost.

In order to cut costs, in summer 2018 ESA issued a call for the provision of a service aiming at de-orbiting an ESA-own debris and also demonstrating on-orbit servicing. Out of the initial set of outline proposals received, ESA encouraged 6 proposers to provide detailed proposals. Out of the second round of evaluation, the proposal from the CLEARSPACE consortium was accepted and negotiated. The mission, called CLEARSPACE-1 by the consortium and ADRIOS by ESA, will demonstrate the deorbiting of a VESPA upper stage.

In the meantime the EC, through the H2020 programme managed to demonstrate some critical technologies at low cost.

In the spectacular on-orbit demonstration of the RemoveDEBRIS project, a chaser satellite released and re-captured two cubesat-class target satellites to demonstrate a variety of ADR technologies such as net/harpoon capture, towing and finally passive deorbiting by means of balloon.

RemoveDEBRIS has been a remarkable success of how technology initially conceived at ESA was actually demonstrated in a EC programme.

2 PLANETARY ROBOTICS

2.1 Mars

The ESA ExoMars mission makes substantial use of A&R[1], in the form of an autonomous rover, an automated exobiology laboratory and a robotised drilling system. The ExoMars programme is a joint endeavour between the Roscosmos State Corporation and ESA. It includes a Russian-provided lander and a rover provided by ESA. The mission, slated for launch in June 2020, due to technical issues and the outbreak of the COVID-19 epidemic, has had its launch postponed to June 2022.

With Ministerial conference of November 2019, the ESA member states have approved initial funds for ESA's participation to the NASA mars Sample Return mission. The contribution of ESA is in three areas, the Earth Return orbiter (ERO), an electric propulsion spacecraft, and 2 robotics elements, the Sample Transfer Arm (STA) and the Sample Fetching Rover (SFR).

The SFR is meant to be a small platform with very high traverse requirement (in the order of 15km), in order to fetch cached samples back to the Mars lander. At the mars lander the STA will be tasked to collect the sample retrieved by the SFR and transfer them into the Mars Ascent Vehicle (MAV).

The SFR development is currently undertaken by AIRBUS SD Ltd. (UK) while the STA development is entrusted to two competitive teams respectively led by LEONARDO (IT) and OHB (DE).

2.2 Moon

ESA intention to independently perform a Lunar mission involving robotics elements goes back to the LEDA - Lunar European Demonstration Approach in 1995 . More recently (2012), the Lunar Lander Programme did not receive funding for Phase B, so it had to be cancelled. The programme included a DLR-contributed small rover tasked to deploy instruments in the surrounding of the lander.

Following the cancellation, ESA continued to pursue the participation to an international Lunar mission. The missions considered at the moment are in cooperation with Roskosmos, whereby ESA would contribute a drill system (derived from the ExoMars one) for the collection of frozen regolith, in addition to contributions to the navigation and communication systems.

The Roskosmos missions are Luna Glob Lander (soft landing technology and study of South Pole region), Luna Resurs Orbiter (global orbital studies), Luna Resurs 1 Lander (for the in-situ analysis of southern pole frozen regolith), Lunar Resurs 2 Sample Return (for the return of southern pole frozen regolith samples to Earth). The Russian agency devised a moon-going strategy to support the nation's lunar program during the next two decades. According to this grand plan, crews would fly the new spacecraft and land on the moon, concluding with the establishment of a modular habitable moon base.

ESA has evaluated the participation to these missions through CDF studies, and it has initiated phase A industrial studies. Considering the huge uncertainty and difficulties connected to the return of pristine samples to Earth, ESA has also initiated the Lunar Volatile Prospector (LVP) studies, aiming at defining a mission for the in-situ determination of the geographical distribution and characterisation of Lunar pole volatiles. The Package for Resource Observation and in-Situ Prospecting for Exploration, Commercial exploitation and Transportation (PROSPECT) will operate at the surface of the Moon as part of the Russian-led Luna-27 mission in 2022 .

3 BASIC ROBOTICS TECHNOLOGY AND AI

3.1 Manipulation systems

The ERA (ESA) robotic arm for ISS is presently the only flight-ready A&R system available in Europe. ERA would have flown to the ISS in 2020 however COVID19 has likely, once again created a delay.

The ESA "Dexterous Robot Arm" (RUAG, Dutch Space, LEONARDO, Tecnomare, HTS, SENER) , , has been for long time the only engineering model of integrated space robot arm manipulator available in Europe for orbital use.

The ESA DELIAN development, carried out by LEONARDO has been selected as baseline for sizing the Sample Transfer Arm (STA) to be supplied by ESA to the NASA MSR mission. The STA development is presently carried out by 2 competing teams, one led by LEONARDO, that will use DELIAN heritage and one by OHB.

Another simpler robot arm has been developed by ESA in the activity "Dust Unseating from Solar-panels and Thermal-radiators by Exhaling Robot" (DUSTER) . The robot successfully remove dust from solar panels and other dust-sensitive surfaces on a Martian probe, by puffing CO2 which is brought to adequate pressure by a pump. Two types of high efficiency pumps have been developed and successfully tested in simulated Martian atmosphere. One is a traditional mechanical pump and another is an absorption pump.

At ESA since the demise of the EUROBOT project, the work on multi-arm robots has restarted with the "Multi-arm Installation Robot for Readying ORUs and Reflectors" (MIRROR). This robot will demonstrate the scenario of telescope-mirror assembly, currently pursued by the H2020 PULSAR grant.

Following the need to develop tools to catch and secure debris, a number of capture-tools and debris clamp have been produced.

The company PIAP of Poland, has produced a number of Launch-Adapter-Ring (LAR) capture tool, capable to cope with different LAR designs.

Also in Poland the company SENER has developed, in the frame of the ESA eDeorbit-B1 contract, the design of a clamping mechanism

In Greece, the company HTR has developed under ESA contract the PREDATOR LAR tool. This tool is subject of further development in the ESA GSTP activity "Capture System for Servicing and Debris Removal" (CRUSSADER) that will bring the tool to TRL7.

With respect to grasping prepared satellites, ESA has developed the standard interface ASSIST[2]. Assist is made of a gripper and a grappling fixture. The gripper to be installed on a servicing/refuelling satellite, the grappling fixture to be installed on the satellite to be serviced/refuelled. ASSIST provides the ability to grasp a client satellite by a servicer and through the same ASSIST provide fuel from the servicer to the client satellite. ASSIST has a public design and is intended to become a standard. ASSIST was tested functionally for fuel transfer safety in TV and also in functionally, to guarantee grasping operation, on a air-bearing testbed.

In the recent years there has been also some effort put in Europe in the development of Standard Interconnects (SI), which have been identified as an important aspect in order to facilitate the development of on-orbit services such as on-orbit servicing and assembly.

For reason of completeness it is noted that the first of such SIs was the DLR funded intelligent Space Standard Interface (iSSI) [3], developed up to TRL 5 in the frame of the third development phase of the project iBOSS.

In the H2020 project "Standard Interface for Robotic Manipulation of Payloads in Future Space Missions" (SIROM)[4], which ended in February 2019, a consortium under the leadership of SENER (Spain) pursued the main objective to develop key technologies for a common building-block connector for autonomous robotic systems conducting in-orbit satellite servicing and planetary exploration. The SIROM project ended with the successful demonstration of orbital and planetary cases using SIROM IF as baseline, hence reaching a TRL 3 to 4.

However, in the currently ongoing H2020 operational grants MOSAR, PULSAR and PRO-ACT the standard interface HOTDOCK, introduced by Space Applications Service (B), was selected for further development[5].

3.2 Mobility Systems
Underground Mobility and Sampling

The no-longer pursued Phobos exploration program spurred several technology developments. The company SENER developed in the frame of ESA GSTP-4 the design and breadboard of a surface sampling tool mechanism for low gravity environment. A breadboard was also developed by AVS in the frame of ESA´s MREP program for a Phootprint like mission. The tool is based on the 'carpet cleaner' principle of 2 fast counter-rotating cylindrical brushes, brushing regolith in a top sampling chamber.

Another sampling tool was made by CBK-PAN in Poland. The tool called PACKMOON[6] was developed under ESA TRP contract up to TRL4. The tool is based on two clamshells that are hammered together to form a hemispherical 'bucket' where the sample is collected.. The tool will be subject of another ESA E3P-EXPERT activity, "Development of ISRU Gear for Generous Excavation of Regolith" (DIGGER) which will assess the usability for small scale ISRU stock acquisition.

Finally another tool for surface sampling in Phobos conditions, was developed by LEONARDO. This tool is based on a large coring driller, with external auger, and clamshell shutters.

For what regards underground access Selex Galileo with SENER and Tecnomare have advanced the development of the EXOMARS drill[7], within the ESA ExoMars project.

After many years, following ESA's autonomous mole for deep exploration[8] (Tecnomare and CISAS), ESA has started a new activity for accessing deeper underground. In the frame of the ESA TDE activity "Drill for Extensive Exploration of Planetary Environments by Robots"(DEEPER) the university of Glasgow is developing a coiled drill system, based on ROLATUBE technology that will reach down to 20m. The drill will achieve TRL3 (but with extensive field tests) by end of 2021.

Surface Mobility

Thanks to the ExoMars mission there has been quite some work in space rovers.

Under ExoMars Project funding, TAS-I (IT), RUAG (CH), ASTRIUM (UK), vH&S (DE), DLR/RM (DE) and MDA (CA) have produced/worked on 3 different models of the ExoMars rover prior to the production of the final PFM. The ExoMars rover has been readied for launch in June 2020, however for risks related to malfunctioning of lander equipment and in combination to the COVID19 epidemics, the launch has been postponed to 2022. The rover will be stored, after some preventive maintenance work, till the new launch campaign begins.

ESA participation to the MSR mission has created a new opportunity for rover development. The Sample Fetching Rover[9] is being designed by AIRBUS UK, under ESA contract. The development is done under considerable time pressure to meet delivery of the flight model to NASA in 2025.

The SFR will use elastic shape-memory-alloy mesh wheels provided by NASA Glenn Research Centre[10] which at the present have higher TRL than ESA's AWE ones.

ESA, recognising that there is a recurrent problem in wheeled rovers has launched and successfully completed the Adaptable Wheels for Exploration (AWE) project.

Rovers for planetary exploration greatly benefit of large wheels, that reduce sinkage, lower the risk of becoming sand-trapped and make locomotion efficient. However accommodating large wheels in a landing craft has proven impossible as the small volume allowance could not fit the wheels.

AWE has produced breadboards of wheel that can alter their shape and go from an initially compact configuration (easy to accommodate in a lander) into an expanded configuration (that provides excellent Trafficability performance). The AWE are top-loaders, wheels unlike previously studied expandable wheels (the INTAS[11] one are all bottom-loaders) so they provide an excellent carried-load/wheel-mass ratio.

Aside from the classical wheeled rovers using articulated bogies and wheels, more exotic and performing leg-wheel systems are possible.

Simple, yet effective robot-wheels combinations are when legs are instead put at the end of wheels. The first known example was the ESA PROLERO robot[12] which has been followed by the RHEX[13] and WHEGS[14]. DFKI (DE) developed from these early concepts the ASGUARD[15] series of robots. While ASGUARD is a terrestrial robot, specific space aimed robot such as CESAR[16] (ESA funded) and COYOTE[17] (EC funded), were also derived from the same locomotion plant.

With respect to a more radical departure from wheels, there is no shortage of terrestrial walking robot developments. The state of the art developments of Boston Dynamics SPOT[18] and similar, is matched by developments in Europe such as at ETHz (CH) with ANYMAL[19] and IIT (IT) HyQ series[20].

However, these are walking robots born and meant for terrestrial use. Space agencies have also funded walking robot developments specifically for space.

ESA and DLR have jointly funded the development at DFKI Bremen (DE) of the SPACECLIMBER walking robot[21],a Semi-Autonomous Free-Climbing Robot for the Exploration of crater walls and bottoms.

While the development of physical robots has advanced, ESA has recognized that the logical ability of walking robots to negotiate heavily cluttered terrains (such us those found in cliffs, crater ridges and caverns) is lagging. Therefore the Autonomous Non-wheeled all-Terrain rover (ANT) technology development was launched in 2020.

Finally, walking robots are attractive for locomotion in low gravity. The SPACEBOK[22] legged robot has been developed by the ETHz (CH) in co-funding from ESA. SPACEBOK is intended to perform controlled jumps in order to move effectively in low gravity bodies.

3.3 Perception

Sensor integration

The I3DS[23] platform (Integrated 3D sensors) was developed in the H2020 SRC operational grant led by Thales Alenia Space SAS. It is a generic and modular system answering the needs of near-future space exploration missions in terms of exteroceptive and proprioceptive sensors with integrated pre-processing and data concentration functions.

Perception Processing

In the ExoMars programme two autonomous navigation systems will be embarked in the rover. The visual motion estimation (VME) prepared by Scisys and CNES achieve performances of relative localisation error (1 sigma error) of less than 1% in position and 1,5% in attitude after a 100m traverse.

In the H2020 SRC operational grant InFuse[24], which ended in January 2019, the aim was to develop very essential data fusion capabilities (aka. Common Data Fusion Framework, or CDFF) that will serve in the context of many space robotics applications, on planetary surface as well as in orbit or other microgravity environments.

Besides the software based solution, ESA has pursued the developments of high-performance low-energy visual Navigation and Localisation with the SPARTAN/SEXTANT/COMPASS[25] activities, implemented by GMV (ES), Democritos University of Thrace (GR), FORTH (GR) and NTUA (GR). These developments produced a very fast and very minimalist computer vision system by using Field Programmable Gate Arrays (FPGAs).

3.4 Control, Autonomy and AI

Following ESA “Goal Oriented Autonomous Controller” (GOAC), "GOAC TRL Increase Convenience Enhancements Hardening And Application Extension” (GOTCHA), the H2020 ERGO[26] project integrated a goal-oriented robotic controller that was demonstrated in a spectacular field trial in Marocco.

The objective of ERGO (European Robotic Goal-Oriented Autonomous Controller) was to deliver the most advanced but flexible space autonomous framework/system suitable for single and/or collaborative space robotic means/missions (orbital and surface rovers) demanding robust operations with adaptable levels of autonomy. Due to the intrinsic similarities of addressed scenarios, especially for what concerns surface applications, ERGO has to be and has been thought so to be applicable to terrestrial robotic applications requiring high level of autonomy.

The achievement of ERGO are being extended in the follow-on H2020 projects ADE[27] and pro-ACT**Error! Bookmark not defined.**

At ESA, following the work undertaken in the TRP project MASTER[28] the project NOAH and NOAH-H[29] have not only created a system for autonomously analysing Martian scenes and detect anomalies, but also have built a large (5000 pictures) annotated database offered to the community of Martian AI researchers.

3.5 Human-robot Interaction

Teleoperation

ESA has developed haptic devices for teleoperation (the ESA Exoskeleton) with in-house work[30] and with SPACE APPLICATIONS SERVICES (BE) and Danish Aerospace Company (DK) in the SPOC development[31].

The haptics teleoperation devices produced by the ESA HRI laboratory have been used in a number of experiments involving the ISS. While the Haptics-1 and Haptics-2 experiments used a purpose-built 1-DOF haptics controller, the following ANALOG-1[32] embarked a qualified version of the Sigma-7 master haptics device from Force Dimension (CH).

For what regards less immersive teleoperation, the HRI[33] developed by DLR/RM (DE) for the METERON SUPVIS JUSTIN experiment has shown to be extremely effective. The hand controller is based on a touchscreen tablet that provides a very simple context sensitive interface, which provides to the astronaut controlling a robot the robot operations that are possible for the objects in front of the remote robot.

HRI for planning and monitoring

The ExoMars Rover Operation and Control ad Centre has the highest TRL of any control and monitoring systems developed for rover operation control and monitoring in Europe. The ROCC developed by ALTEC (IT) and TRASYS (BE) uses many years of technology developed by ESA in various activities (FAMOUS, MUROCO, 3DROV, 3DROCS[34]).

The integration of teleoperation and planning/monitoring HRI has been implemented in a number of ESA activities such as LUCID[35] and RACER[36] which aimed both at operating efficiently rover assets in the semi-shadowed areas of the Lunar poles.

3.6 Robot Ground Testing

Analogue Field Tests

It has now become established that to test the effectiveness if not the fitness of a rover system to act as exploration means, field trials must be undertaken.
Field test campaigns have been undertaken by the HRAF-2 and by the EXOFIT[37] activities in support to ExoMars.
Analog tests can also be developed when suitable environment is not found, by creating ad-hoc analogs. The company PIAP constructed a complete lunar pole terrain in a quarry in Poland to conduct the ESA RACER tests[38].
More recently the Morocco field test, organised by the H2020 FACILITATORS[39] was the largest field test ever organised by European entities.

5 CONCLUSION

This paper provides a status of the many activities running in ESA and in the European Union H2020 program since the last i-SAIRAS. It is hoped that it explains the relationship to the many papers submitted to i-SAIRAS 2020 by the implementers of these activities.

It should be noted that the European Space Robotics field has many more actors than ESA and the EU H2020, however the treatise of the vast number of activities undertaken by all European actors would have exceeded the length of papers allowed to i-SAIRAS.

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