EVE: A Preliminary Study of an Autonomous Robotic Assistant for Plant Cultivation in Future Lunar Greenhouses

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***Abstract*— The German Aerospace Center (DLR), as part of the International Space Exploration Coordination Group (ISECG), shares the vision of sustainable human and robotic exploration of the Solar System. In this context, the EDEN LUNA project introduces a Moon-analogue greenhouse facility for the demonstration of nearly closed-loop bio-regenerative life support systems technology and plants cultivation for the purpose of feeding a crew. An autonomous robotic system EDEN Versatile End-effector (EVE) is to be integrated into the EDEN LUNA greenhouse, to partner with humans in support of this food production and to enable sustained extra-terrestrial exploration. EVE operates in a shared-autonomy manner, wherein an operator issues commands which trigger autonomous operation of robotic system. This is a highly significant feature which directly impacts the workload of astronauts inside the greenhouse. This preliminary study describes the design of EVE and compares EVE's preliminary performance to existing studies on agricultural robotics. It also investigates space plant cultivation experiments and ground-based greenhouse analogues to compare them with the automatized scenario presented in this work.**

I. INTRODUCTION

The Global Exploration Roadmap (GER) exploration goals [1] foresee in-situ food production for astronauts to support long-duration missions. This will enable sustained living and working on the Moon, reducing logistics costs and providing the necessary nutrients to the crew diet.

Greenhouse operations traditionally rely on crew time. However, in extra-terrestrial missions there are several situations where humans will not be available for this task, e.g.: during the initial crew-minimal phase when continuous human presence is not expected, periods when crew time needs to prioritize scientific activities, and in a scaled-up scenario wherein several greenhouses are employed and it becomes impractical to allocate the whole crew to operations and maintenance of all of the agricultural units.

The EDEN LUNA greenhouse, just one part of the EDEN lunar analogue facility, is a ground demonstrator for future extra-terrestrial operations. The autonomous robotic system EDEN Versatile End-effector (EVE) is incorporated into the EDEN LUNA greenhouse to support the plant cultivation activities and to cover critical situations such as those listed above. The ethos of this facility aims to aid and promote the health of EVE's human colleagues, and this collaboration respects the positive impact on the crew's mental health caused by horticultural activity.

The potential benefits of automating plant cultivation tasks have been discussed in [2], [3], and [4]. Several studies – e.g. [3], [5], and [6] – describe the application of the robots in agriculture on Earth or space analogues with dedicated plant cultivation area operated only by humans. However, there is a lack of literature on automated indoor agricultural systems and on the impact of share-autonomy on crew time and well-being.

While robots in agriculture are not a new phenomenon – e.g. [7], [8], and [9] – robots used in plant cultivation are typically highly specialized for a given task – typically handling only one type of plant or a well defined task – and highly constrained environments are uncommon. By contrast, the current vision for extra-terrestrial green houses [5][6] maximize growing space while allowing for the space required for life support critical systems, providing only a minimum operational space for an astronaut or a robot to maneuver and interface with the cultivars.

EVE leverages DLR robotics heritage – including but not limited to space manipulators [10], manipulating delicate objects [11], light weight robotic arms with a high degree of manipulability [12], and shared autonomy [13] – to fill this gap. This paper introduces EVE and provides some results from its initial testing phase. The aim of this paper is to reinforce the benefits of the use of autonomous robotics in a lunar greenhouse environment comparing it with the crew time in space analogue missions or real space missions.

The remainder of this paper is structured as follows: Sec. II provides a brief overview of the requirements and challenges faced in extra-terrestrial crop cultivation. Sec. III outlines the EVE robotic system. Some preliminary perception and harvesting tests are presented and discussed in Sec. IV. Finally, Sec. V provides a conclusion with a look towards the future.

II. Requirements and Challenges for Agricultural Robots

Agricultural robots on Earth, like those pictured in Fig. 1, come in many forms, and work in parallel to perform a variety of tasks. Several studies in agricultural robotics which consider the harvesting task in an open field or in large greenhouses exist – [7], [14], [15] to name but a few. Strawberries, tomatoes, apples, sweet peppers, kiwi, and

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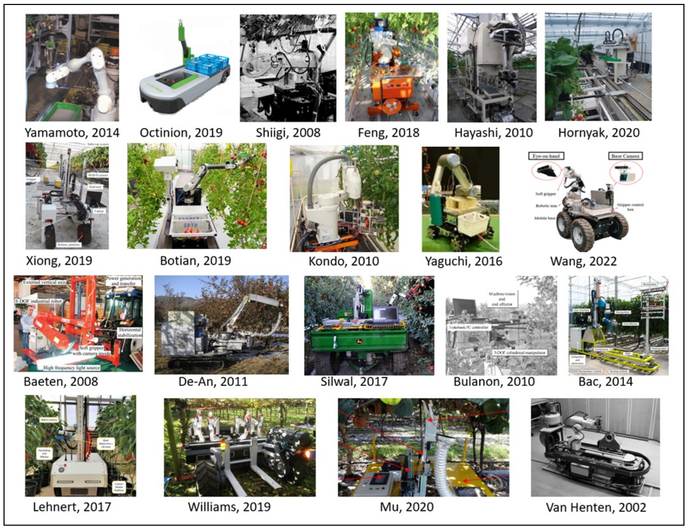

Fig. 1: Different agriculture robots developed for Earth applications. Photo credits, in order of appearance: [7], [8], [9], [14], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [16], [28], [29], [30], [31].

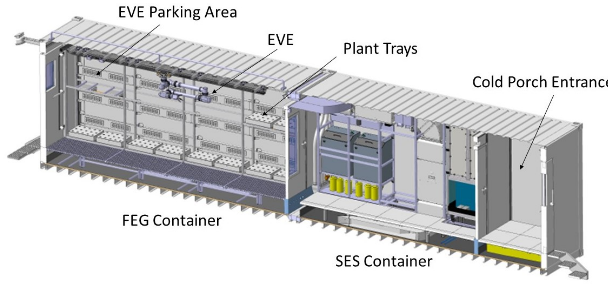

Fig. 2: EDEN LUNA Greenhouse.

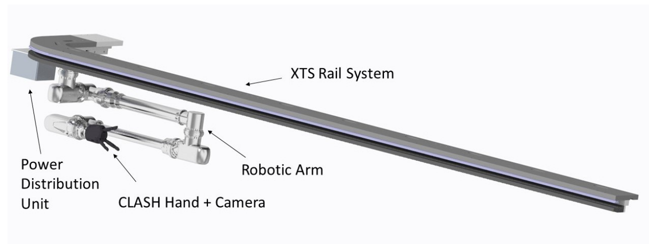

Fig. 3: EVE robotic system.

cucumbers are some of the more popular crops considered in these publications. The environment where the task is carried out impacts the mobility of the robot. The width of the alleys and the distribution of the plants determine how constrained the site where the robot operates is. These terrestrial robotic systems are developed to completely replace human work in the cultivation workspace. The robot architectures range from wheeled to guided rail solutions and their end-effectors can be grippers, cutters, suction devices or crop specific picking tools. A comparison of the architecture and targeted cultivars of the robots presented in Fig. 1 is provided in Table I.

In the course of their work, it is required that the robots interface with and harvest cultivars, but should not cause unnecessary damage to plants or infrastructure and should lose as little produce as possible. Successful harvest rate, cultivar damage rate, and the total time to harvest one cultivar are therefore the performance parameters most frequently analyzed to evaluate the suitability of an agricultural robot [16]. A comparison of these parameters for the systems presented in Fig. 1 has been presented in [4].

NASA reports that one hour of crew time in space costs approximately USD $130,000$ [32] - i.e. each minute costs USD $2,170$. Understanding the work time necessitated from the crew is therefore crucial in planning how it should be spent. Additional parameters for considering crew time spent processing a given area of cultivars are therefore traditionally used to evaluate extra-terrestrial agricultural experiments and analogues. The records of these metrics for the investigations reported in [3], [5], [6], [33], [34], [35], [36], [37], [38], [39], and [40] are presented in Table II. It is important to note that these experiments and analogues have thus far only considered 100% crew cultivated plants.

EDEN LUNA is the first ground-test demonstrator which incorporates a robotic assistant into plant cultivation. The architecture of the demonstrator recycles much of the design of EDEN ISS [5] [6]. It is composed of two enclosed spaces, housed in a pair of two interconnected 20 foot shipping containers. The Future Exploration Greenhouse (FEG) is the greenhouse test facility, which supports $12.5\ \mathrm{m}^2$ of growing space. EVE resides and functions exclusively in the FEG. The Service Section (SES) houses support systems and workspaces. Fig. 2 depicts the interior of the greenhouse. All life support systems needed for the cultivation of plants in space are incorporated into this structure. Fig. 2 indicates the available workspace for cultivating plants within it.

The available working area is clearly highly constrained. Power restrictions and qualification requirements place further limitations on the robotic assistant. The robot design and construction must account for these constraints. The agricultural robotic assistant has a further balancing act to contend with. Unlike existing terrestrial systems, the robot must also be highly versatile, handling a variety of cultivars with limited crew intervention so as to permit crew to flexibly engage in more valuable tasks. However, extra-terrestrial cultivation is itself an area of research and crew value direct interaction with cultivars when possible – the robot should therefore not prevent astronauts from interfacing with the cultivars. The robot therefore needs to be fully stowable or otherwise not impede astronaut access to the corridor.

III. The EDEN Versatile End-effector

In this section, the hardware, autonomy approach, perception methodology, control, and operation of EVE are presented.

A. Hardware

The EVE hardware, illustrated in Fig. 3, is composed of several subsystems, namely: a linear rail system, a 7-DOF manipulator, a gripper, a camera, a power distribution unit, and an industrial PC. An early design was presented in [43].

TABLE I: Design of agricultural robots.

Robot	Manipulator	End-effector	Mobility	Target Environment	Crop	Successful Harvest [%]
Yamamoto [7]	4DOF	CS	S	LS	strawberry	67
Octinion [8]	3DOF	CSG	WMP	WGH	strawberry	70-90
Shiigi [9]	3DOF	CGCS	WMP	WGH	strawberry	38
Feng [14]	6DOF	CGC	WMP	WGH	strawberry	83
Hayashi [17]	3DOF	CGCS	WMP	WGH	strawberry	41
Shibuya Seiki [18]	3DOF	CGCS	WMP	WGH	strawberry	54.9
Xiong [19], [15]	2 x 3DOF	CRG	WMP	WGH	strawberry	53.6
Botian [20]	6DOF	CRG	WMP	WGH	tomato	85
Kondo [21]	4DOF	CGC	S	WGH	tomato	50
Yaguchi [22]	6DOF	CSG	WMP	WGH	tomato	60
Wang [23]	6DOF	CSG	WMP	FO	tomato	70-85
Baeten [24]	6DOF	CGS	WMP	FO	apple	80
De-An [25]	5DOF	CGC	WMP	FO	apple	77
Silwal [26]	6DOF	CRG	WMP	FO	apple	57
Bulanon [27]	3DOF	CRG	WMP	FO	apple	90
Bac [16], [41]	8DOF	CCS	WMP	WGH	pepper	29.5
Lenhert [28]	6DOF	CCS	WMP	WGH	pepper	58
Willians [29]	4 x 3DOF	CRG	WMP	FO	kiwi	51
Mu [30]	3DOF	CRG	WMP	FO	kiwi	90
Van Henten [31], [42]	6DOF	CGC	WMP	WGH	cucumber	80

CRG = Customized Rigid Gripper; CSG = Customized Soft Gripper; CGC = Customized Gripper and Cutter; CGS = Customized Gripper and Suction; CGCS = Customized Gripper, Cutter and Suction; CCS = Customized Cutter Suction; CS = Customized Suction; S = Stationary; WMP = Wheeled mobile platform; WGH = Warehouse-size greenhouse; FO = Fruit orchard; LS = Lab-Setup

TABLE II: Crew harvesting statistics for different missions.

Mission	Crew time/day (min)	Growth Area (m^2)	Crew time (min/day/m^2)
ISS Veggie	2.8	0.13	21.5
ISS APH	2.8*	0.2	14*
HI-SEAS II	15.6	0.5	31.2
MDRS	45	5	9
ILMAH	12	0.5	24
EDEN ISS	143	12.5	11.5
BIOS 3	600	37.5	16
LP365$^+$	960	58	14.6
SPFGC	204	11.1	18.4

*Values based on similar experiment on ISS Veggie; $^+$Lunar Palace 365 [38], [39]

The full system is designed to be mounted to the topdeck of the support structure of the FEG container, such that the manipulator can move along the rail subsystem through the corridor illustrated in Fig. 2 to interact with a given cultivar in the plant support structure. To permit this corridor to remain clear when crew need to access the space, the robot is stowed in a designated area, noted in Fig. 2 as the ”EVE Parking Area”. The subsystems are selected from a variety of off-the shelf and DLR heritage systems, as outlined in the following.

The linear rail subsystem is a Beckhoff eXtended Transport System (XTS) rail system. It is assembled in an L-shaped configuration and possesses 22 modular motors. This allows the robotic arm to be stowed in a parking area when not in operation. Two magnetic movers hold the arm, hand and camera while a third mover sustains the power distribution unit. These three movers move along the 5-m extant of the rail enabling the manipulator to reach any point of the greenhouse.

The robotic arm is a revision of the TINA Arm [12] and is part of the DLR heritage of low-weight manipulators. It has 7-DOF which ensures high manipulability and high dexterity during its operation. This is advantageous for the very constrained space of the EDEN LUNA greenhouse. In contrast to half of the presented existing terrestrial agriculture robots (Table I) which opt for a low degree of manipulability (3 or 4DOF), the versatility of the 7-DOF TINA arm can also be employed in other future assistive applications within the FEG such as cargo tasks, infrastructure assembling, and scientific activities. Versatility is key in such complex lunar missions and the risk of not accomplishing the task imposed by limited systems is not desirable. Several publications reported that the robot could not harvest all of the targeted fruit because they were out of reach of the robotic arm [19], [15], [29], [24] or the approach of the end-effector to the fruit was limited by the manipulator [21], [27], [14].

The gripper subsystem is also selected from DLR heritage systems. The CLASH Hand [11] is a three-finger robotic hand which is designed to manipulate soft objects. This is possible due to its variable stiffness and the tactile piezoresistive sensors on its finger tips. With the ability to control the contact forces to avoid damaging the target object, the CLASH hand is highly suitable for the harvesting task. Unlike the vast majority of the end-effectors presented in Table I which are customized for only one type of fruit, the CLASH has been successfully validated with objects of

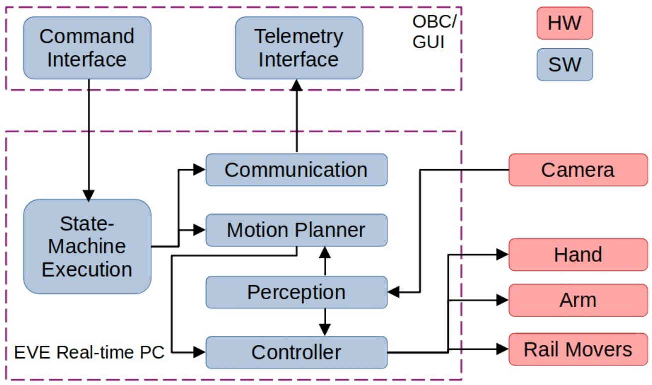

Fig. 4: Software Architecture for Shared Autonomous operation.

different shapes, sizes, and colors [11].

The camera subsystem is an Intel Real Sense D435i and capture RGB and depth images for the perception algorithm. The industrial PC manufactured by Beckhoff contains the software architecture which controls and operates the EVE system autonomously.

B. *Shared Autonomy*

The EVE system operates in a shared autonomy manner. This concept is defined by the distinction between the operator and the robot responsibilities. While the human is responsible for the high-level goal the robot takes care of the low-level task [44]. Rather than operating the robot during the entire task execution, the operator only initiates the operation with a task definition and a subsequent command. From this point, EVE autonomously carries out a series of actions to accomplish the task.

The software architecture used to achieve this is summarized in Fig. 4 [4] [43]. A remote computer interface is on the operator side while a dedicated real-time computer is local to the robot. A command sequence dispatched by the user reaches the real-time machine which includes a hierarchical state-machine execution block, a motion planner, and a controller. The state-machine coordinates the numerous robotic skills needed to accomplish the harvesting task. The motion planner calculates the optimal trajectories to bring the arm into the region of the target cultivar while avoiding collisions between the robot and the environment, to bring the gripper to the target fruit, and to harvest the fruit. The motion planner relies on the image processing provided by the perception block to approach and harvest the cultivar. Finally, the controller steers the execution of the received motion plans, translating them into real movement of the robot's hardware. All the steps of the operation are monitored via the telemetry received in the user interface.

C. *Perception*

Perception is a key feature of a robotic system, informing both the motion planning and control operations. The images obtained by the camera are processed by the perception pipeline to estimate the pose of the object of interest. The EVE vision pipeline used for the perception task is illustrated in Fig. 5.

The vision pipeline starts with the collection of RGB and depth images (1) from the camera. Detection and segmentation of the fruit are executed using the RGB image. GroudingDINO [45] is used to detect the cultivar, in this case a tomato. This coarse segmentation is represented by the purple square which defines the object bounding box (2). The bounding box is then transmitted to a Segment Anything Model (SAM) [46] and its segmentation mask is defined (3). After that, the depth image is used to calculate the centroid of the segmentation mask (4). The object 3D pose is defined with respect to the camera based on the known parameters of the camera (5). Finally, the position of the object with respect to the robot is provided through a prior robot-to-camera calibration (6) [47]. This relative position calculated by the algorithm is passed to the task manager and controller which will act to execute the grasping task.

D. *Control*

The EVE subsystem maintains a distributed control across each of its component subsystems - rail, robotic arm, and CLASH hand. Each component is required to control its own motion, with a bridge connecting their high level task definition. While this may make the integration of the subsystems more complex, the modular nature allows each subsystem to be tuned individually for its specified task using the tools developed for each of the components and permits preliminary testing at the subsystem level.

The rail system, with its chain of linear motors, relies on a control loop with both position and velocity control [48]. These two control loops can be tuned independently for a precise position control and smooth motion of the movers along the rail. In terms of system integration, this is a key tuning point to ensure that the pendulum nature of the robotic arm subsystem in its parking configuration does not introduce substantial vibration into the movers.

The robotic arm has several operational control modes [12][10]: *Stepper control mode* – open-loop control of the motor space vector for precise positions and velocities. *Torque control mode* – utilizes the measurements from joint torque sensors to regulate the torque output. *Position control mode* – takes the angular state values from the joint Hall sensors, providing accurate position control. *Impedance control mode* – combines, in a cascaded approach, the position and torque control modes to regulate the impedance of the joint, ensuring a compliant behavior, precise positioning, and stability when the arm is interacting with the environment. The option of these control modes permits comparative investigation in this new and highly constrained environment of application.

The CLASH Hand utilizes an updated revision of Variable Impedance Actuation (VIA) [49] implemented in its fingers. VIA control allows the hand to vary the stiffness of each finger at constant load. This is an important feature for applications in which a moderate force/torque interaction with the environment is required – i.e. harvesting fruit or

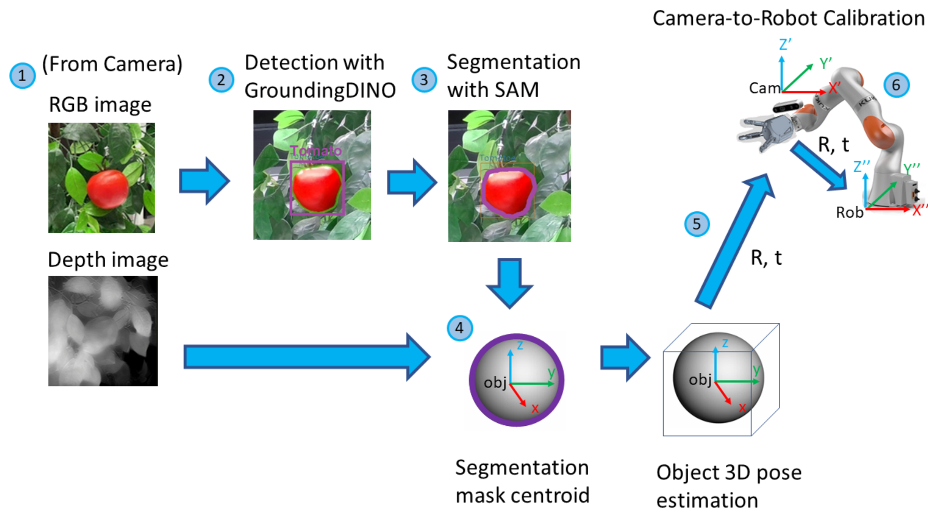

Fig. 5: Diagram of the vision pipeline used for perception.

handling a soft object. The stiffness variation of the fingers is achieved either mechanically, changing the setup of the main mechanical components within the actuators, by the controller [50], or in a combined manner [51].

E. *Operation*

The operational steps for the EVE system to accomplish the harvesting task are displayed in Fig. 6. First, a command is initiated from the operator (H1) to align the robotic arm with the targeted bay within a given shelf of the greenhouse from which the fruit is to be collected. The command encapsulates the information about the target bay location and the type of task (monitoring or harvesting) to be executed by the EVE system. Then, the rail mover and the manipulator motion (H2 & H3) is computed, considering the best trajectories to achieve the correct position without colliding with obstacles inside the greenhouse. The execution of this controlled movement is carried out (H4 & H5), tracking the path generated by the motion planner. With the manipulator in position, the pose of the targeted fruit is identified (H6) and the manipulator motion is planned (H7). The final adjustment to the manipulator configuration is executed (H8) and the hand closes its fingers with the correct force to harvest the tomato (H9). The tomato is detached from the branch and transported to the storage shelf where all the harvested fruits are placed (H10). When the hand opens its fingers the tomato is released (H11). Finally, the EVE system is ready for next task (H12) in stand-by mode.

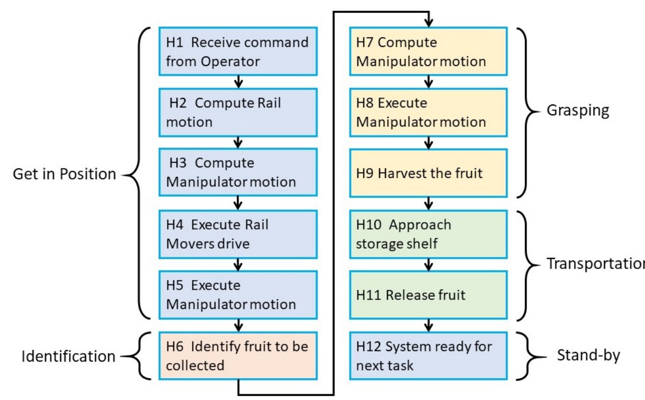

Fig. 6: Operational steps for the EVE system for the harvesting task.

IV. Preliminary Experimental Campaigns

Three preliminary functional harvesting tests have so far been conducted during the development of the EVE system. These tests have considered the functionality of the perception pipeline and the use and motion of the gripper in harvesting cultivars. The cultivar of concern in these tests were ripe medium sized tomatoes – e.g. Lyterno F1 tomatoes commonly available at the supermarket, approximately $4-8$ cm in diameter.

The experiments were designed with the following aspects in mind: As noted in [11], the CLASH Hand was developed for handling delicate objects, and therefore the ability of the hand to handle fresh fruit was not of immediate concern. However, as the experiments at this stage of the project were to be conducted in a functioning robotics lab, prudent health and safety measures must be abided by. Finally, sustainability in space begins with sustainability in the lab. Using artificial fruit permits high volume testing and the sustainable generation of a non-static test field, allowing some variance in resetting the scene over the numerous trials.

The first functional test evaluated the ability of the perception algorithm to successfully identify tomatoes within a plant. As illustrated in Fig. 7, fruit can easily be obstructed by leaves or other detritus, the typical round outline and high contrast to the environment can be antagonized. In Fig. 7 it is possible to see that all of the tomatoes are individually identified even when they are partially occluded by leaves or by a nearby tomato. This is a positive outcome considering that this occlusion situation is one of the most common challenges in agriculture robotics as reported in [7], [16],

Fig. 7: A test identification of a cluster of tomatoes on the vine. Three tomatoes are in full or partial view of the camera. In this case, all three are correctly identified, as indicated by the respective masks and labels.

Fig. 8: An artificial tomato used in the preliminary tests (left) and a locally sourced fresh tomato (right). For perception purposes of this test, they are functionally identical.

and [28]. An artificial fruit, depicted in Fig. 8, was also designed for use in the next preliminary test. The perception algorithm was further shown to successfully identify the artificial fruit as a tomato. The selected artificial fruit are sufficiently comparable to readily available fresh tomatoes, see Fig. 8, and a comparable motion of the hand is required to detach each from the plant.

With this success, Harvesting Test I, presented in detail in [4], used exclusively artificial fruit in a total of 36 harvesting trials. The trials were organized such that the artificial plant initially had six fruit to be harvested, and the plant was fully de-fruited six times. The plant was placed on a tray ($0.78m^2$) in a shelf of identical size as will be used in the FEG. This preliminary test recorded harvesting success rate of 58.3%, drop rate of 36.1 %, and fail rate of 5.6%.

Harvesting Test II followed, limited to two clusters of four and three real tomatoes. Temporary safety measures were taken to ensure safe laboratory conditions were maintained. For the removal of the tomato from the vine, a slightly modified motion of the gripper was implemented: a 90-degree rotation of the last joint of the manipulator was added after the CLASH hand grasped the target fruit. This procedure enabled an accurate detachment of the tomato from the vine. The sequence of images in Fig. 9 depicts this operation in the successful harvest of a tomato.

TABLE III: Performance rate for EVE in Harvesting Tests I & II.

Test	Run	Cycle time (s)	Success (%)	Drop (%)	Fail (%)
Test I	36	23.46 ±1.62	58.30	36.10	5.60
Test II	7	25.39 ±3.88	71.00	14.50	14.50

The results for Harvesting Test II are summarized in Table III. In this test, the success rate was 71%, drop rate 14.50 %, and fail rate 14.50%. It is also noted that the average cycle time for Test II is nearly two seconds slower than that for Test I. This is explained by the additional rotation on the last joint of the robotic arm which allows the detachment of the tomato from the vine.

A. Discussion

The harvesting test results indicate a similar successful grasp rate of fruits for the CLASH hand (58.3 % on artificial fruit in Harvesting Test I and 71 % on real fruit in Harvesting Test II) as that for existing agricultural robots (64.4 %, refer to Table I). Based on the harvest cycle rate results, EVE can be expected to harvest tomatoes at a rate of 11.6 min/day/m^2, which is equivalent to the fastest performance rates of humans in space analogue experiments and in space missions (9 and 11.5 min/day/m^2 for MDRS and EDEN ISS, respectively, refer to Table II) – demonstrating that the robot can do the task as efficiently as the crew, permitting them to focus on other priority tasks with the knowledge that their supply of tomatoes is secure.

However, these remain preliminary results for only one cultivar, and there are several key points for development as the final stages of the project are approached. While the average cycle time for terrestrial harvesting robots is comparable to the experimental values in the current state, this is an evolving metric which will change as further system integration, refinement of the motion planning algorithm, and integration of additional cultivars occur. Modifications on the orientation of the hand as it approaches the target tomato are necessary for a more accurate grasping. This is also linked to the perception of leaves and branches. If the perception algorithm can understand the position of the leaves in relation to the target fruit, an adaptive orientation of the hand can be used to avoid imperfections on the execution of the grasping task.

V. CONCLUSIONS

The development of a sustainable food chain is imperative for the continued trajectory of extra-terrestrial exploration. This paper has presented EVE, a robotic assistant for future lunar greenhouses. An overview of EVE's subsystems and their integration has been provided. Preliminary study of the perception pipeline and harvesting capabilities of the gripper have been presented.

Integration of the EVE subsystems continues at the DLR Institute of Robotics and Mechatronics. Further integration and commissioning studies will be conducted before final

Fig. 9: Sequence with CLASH hand grasping the real tomato.

integration within the EDEN LUNA facility occurs in the near term.

It is important to acknowledge that harvesting fresh produce is not the only task to be done in an extra-terrestrial greenhouse. Harvest is only the middle of the cycle. For example, seedlings and sprouts also require eventual relocation into their growing tray and harvested produce require delivery and proper storage techniques. Eventually, it should be expected that a robotic greenhouse assistant can be relied upon to do additional tasks, like plant health monitoring or even light maintenance of its environment. These are good candidates for telepresence tasks, where a human operator on Earth can work with a robotic assistant to obtain and process information. All of these questions may not be answered in the framework of EDEN LUNA, but EVE pioneers the development of extra-terrestrial agricultural robots and influences the discussion of future lunar greenhouses.

ACKNOWLEDGMENT

The authors and the entire EDEN LUNA project team acknowledge and thank the government of North Rhein Westphalia for the funds received to finance the outfitting of the LUNA facility and the development of EVE. We also thank all of the colleagues not mentioned in the author list and partners who have contributed to this project.

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