Shared control for robotic on-orbit servicing

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***Abstract*—A shared control approach is proposed to reveal the synergies of visual servoing and telepresence in a robotic on-orbit servicing scenario. Both methods, visual servoing and telepresence, have their respective strengths and are subject to challenges for the task at hand. In a shared control approach, the advantages of a human operator in the loop, its ability to react and adapt to unanticipated and versatile change of conditions, outlast. While the visual servoing, for a controlled range of conditions, has the ability to achieve the task autonomously and, running on-board, without performance degradation due to the communication delay. In the proposed approach, the autonomy module can support the operator and reduce his workload. Already implemented as well as future features and ideas are presented in the following.**

I. INTRODUCTION

On-orbit servicing (OOS) capacities are in immediate demand with the expansion of space debris and the number of objects in orbit, in general, [13]. While the implementation of new space policies can help to slow down the increase, debris mitigation has been identified as key factor to contain a chain reaction of collisions, fragmentation and new impacts. As seen on-ground, robotic technology is one of the most versatile tools for a wide range of tasks and scenarios. Furthermore, the robotic on-orbit servicing capabilities can be used for servicing tasks on still functional satellites, e.g. refueling and replacement of modules, potentially reducing costs and risks. For example the Hubble Space Telescope's original costs of \$2.5B raised to \$10B (as of 2010), mainly due to four manned servicing missions [6].

Involved in several mission design phases, the application of two key technologies, telepresence and visual servoing has been analyzed and developed.

Visual servoing has been found crucial to achieve the necessary end-effector positioning accuracy to successfully capture a target satellite in several scenarios. One of the main challenges comes with the measurements based on image processing which is very sensitive to the light conditions. In particular space light conditions can be very challenging. They highly depend on the position of the sun and the relative position of the object to be observed. In addition to drastically and sometimes very dynamically changing light conditions, reflections and specularities on the multi-insulation layer and the solar panels present challenges to the image processing and for simulation/rendering [14]. Telepresence and haptics have been identified as key technologies for space applications and missions like ROKVISS [10] and KONTUR-2 [4] have shown their potential. Significant progress has been achieved in developing methods to deal with the inherent, destabilizing delay in the communication, and different control architectures with the overall goal to maximize user transparency and immersion for increased task performance. The human is best suited to adapt and react to a wide range of possibly unanticipated challenges/changes, e.g. in the light conditions. The performance is limited by and decreases with the increase of time delay, and an increased degree of autonomy becomes necessary. Furthermore, spatial perception, e.g. depth, can be difficult (even in the case of stereo vision), and estimation by size or based on specific image features becomes helpful. For this purpose, image processing techniques can yield accurate results and can thereby reduce the operator workload. It supports the necessary redundancy that is crucial for space missions.

An experimental facility (Fig. 1) has been set up to test and develop control algorithms with hardware in the loop and real contact dynamics under utmost realistic zero-gravity conditions. Further details can be found in [5].

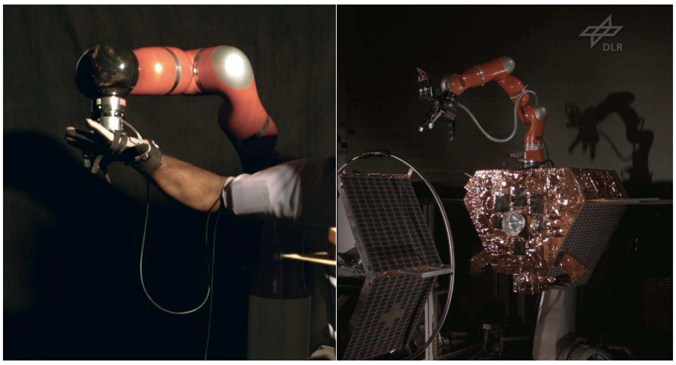

Fig. 1: The teleoperation system in OOS facility.

II. METHODS

In this section, some of the fundamentals of visual servoing and the telepresence methods are presented.

A. *Visual servoing*

To position the end-effector with sufficient accuracy for a successful capture, a pose-based visual servoing scheme with eye-in-hand stereo cameras is adopted. A model-based visual tracking algorithm [9] yields the relative pose between end-effector (EE) and desired pose, the so-called grasping frame, relative to the target. The goal is to align the EE-frame with the grasping frame. Following the classical visual servoing scheme [7], the desired EE-velocity is computed using a proportional gain on the error between the two frames. In order to control the contact forces, the robot is controlled in impedance mode which also allows a straightforward combination with telepresence. To improve the robustness of pose estimation and thereby the overall visual servoing task, an Extended Kalman Filter (EKF) has proven to be a key component of the autonomy module. The implementation of the EKF for the estimation and prediction of the motion of a free-floating target based on quaternions follows [1]. In an extended version [2], also the dynamic parameters of the target, i.e. the inertia, and the geometry, i.e. the orientation and displacement of the grasping frame w.r.t. to the satellite, are estimated/refined. The adoption of a Kalman Filter has advantages for the shared control approach as described in Sec. IV.

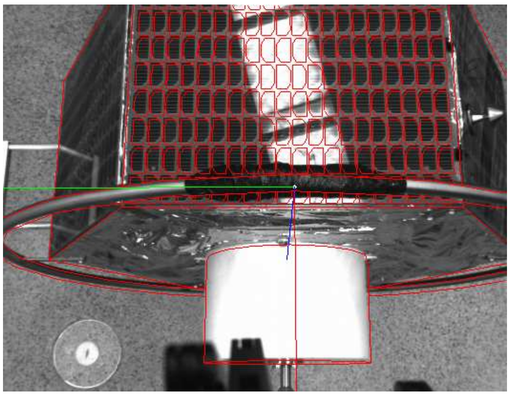

Fig. 2: Left camera view augmented by pose estimation (in red) with desired grasping frame (x-axis in red, y-axis in green, and z-axis in blue).

B. Telepresence

The bilateral teleoperation that enables the remote control of a slave device by a human operator using a haptic interface, through which he feels the interaction forces from the slave has been thoroughly studied in [11], [16]. The main challenge in teleoperation arises due to the time delay between the master and the slave systems which could make the system unstable [3]. Transparency, which is the feeling of immersion into the remote environment obtained by the human operator, as a trade-off for system stability has been discussed in [12] and [16]. Even though several works have dealt with the issues of communication time delays, in this work, the authors propose to apply the Time Domain Passivity Approach (TDPA), a passivity based tool that ensures stability under large delays [15], [4]. A passivity observer monitors the energy flow at both sides of the communication channel. If a generation of energy is observed, a passivity controller in form of a time-varying damping element dissipates exactly the same amount of energy and thereby renders the overall system passive. Fig. 3 shows the 2-channel architecture in bilateral teleoperation augmented with the passivity observers and controllers $POPC_{L,R}$. The blocks $H+M$ and $S+E$ represent the human with the haptic device and, the slave robot in the remote environment respectively. Z_{CS} is the position tracking controller at the slave side while T_f and T_b represent the forward and backward transmission delays. Detailed information on this system can be viewed in [15].

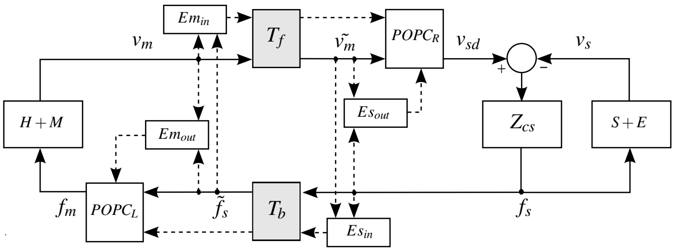

Fig. 3: Block diagram of 2-channels architecture with TDPA

III. COMPARISON OF VISUAL SERVOING AND TELEPRESENCE

Table I shows the influence of several factors, both internal and external sources of errors, on both of the approaches considered. It has to be noted that for all the factors (except prolonged camera failure), the two methods are complementary. This complementarity of autonomy and telepresence is the main emphasis here and also the basis for the proposed shared control.

TABLE I: A comparison between Visual Servoing (VS) and Telepresence (TP). '✓' implies that the method works and '-' implies that the method fails/degrades in performance

Factors		VS	TP
Internal	Force Sensor Errors	✓	-
	Low Camera Resolutions	-	✓
	Prolonged Camera Failure	-	-
	Human Errors	✓	-
External	Light Reflections	-	✓
	Specularities	-	✓
Model Uncertainties	Servicer Kinematics	✓	✓
	Servicer Dynamics	✓	✓
	Target Geometry	-	✓
	Target Dynamics	-	✓
Transmission Factors	Single Image Loss	✓	✓
	Data Black-outs	✓	-
	Delays $<$ 1 sec	✓	✓
	Delays $>$ 1 sec	✓	-

IV. SHARED CONTROL

To realize the shared control scheme, a quantitative measure of the quality of the visual tracking, i.e. the reliability of the pose estimate, is necessary. As Dragan et al. [8] observed, the provided degree of assistance must depend on the robot's confidence. In this work, we consider the confidence in the state estimate, i.e. in the filtered pose estimate or in the predicted value in the case of a pose estimation failure. This quantity can be used to modulate the authority allocation α. The shared control is then implemented as linear blending of the torque input from the visual servoing component τ_{VS} and from the telepresence component τ_{TP}

$$\tau_{cmd} = \alpha\tau_{VS} + (1-\alpha)\tau_{TP}, \ \alpha \ \varepsilon \ [0,1]. \quad (1)$$

A. *Switched*

In the switched approach, visual servoing is adopted for the nominal case ($\alpha = 1$). In case of a failure of the pose estimation during the visual servoing, it is detected automatically and the authority is allocated to the human operator ($\alpha = 0$). This can be done, evaluating the estimated target motion between two consecutive frames. Since the target is known to be free-floating with a relatively low velocity, this motion can be bounded from above. If the estimated motion/velocity is exceeded or the time since the last successful pose estimate reaches a threshold, the autonomous approach is considered to be failed, and the supervisory system shifts the authority. For the handover from autonomy to human operator, it is important that the master device tracks the slave motion during the autonomous approach, so for the handover, both will be in the same configuration/position.

B. *Shared*

A continuous measure of the reliability, is given by the Kalman Filter that is an integral part of the visual servoing system (Sec. II-A). The state covariance P can be considered as uncertainty, or inverse of the confidence. Approaching a defined threshold γ (which is also taken to be the saturation value for the norm $||P||$), the output of the pose estimation/prediction is considered as unreliable and the human operator should take action. The authority allocation can be modulated by

$$\alpha = (1 - ||P||/\gamma). \tag{2}$$

V. CONCLUSION

A shared control approach for the combination of autonomous visual servoing and human-operated telepresence for the capture of a free-floating satellite was presented. A comparison of both modes' advantages and disadvantages under different influences was made, and two different strategies for the combination presented in order to reveal the synergies. Therefor, a quantitative measure was proposed for autonomously shifting or switching the authority. Future work includes a user study with varying conditions that influence the performance of both modes, and the development of a hybrid control approach.

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