

# Tracking Control for the Grasping of a Non-cooperative Tumbling Satellite with a Free-Floating Robot

Roberto Lampariello, Hrishik Mishra, Nassir Oumer, Phillip Schmidt, Marco De Stefano, Alin Albu-Schäffer

**Abstract**—This electronic document is a live template. The various components of your paper [title, text, heads, etc.] are already defined on the style sheet, as illustrated by the portions given in this document.

## I. INTRODUCTION

Robotic systems are becoming more and more of a reality in orbital applications. Of interest here are those which may operate in On-Orbit Servicing and in Active Debris Removal missions [ETS-VII][Orbital Express][DEOS][Cinese mission][eDeorbit]. To tackle the related control challenges we present here an autonomy-based approach, in which the robot is commanded through a precomputed reference trajectory, corrected by a tracking controller, to account for intrinsic planning and execution errors. We focus on the task of grasping a defective, tumbling target satellite (from here on, the Target) by means of a free-floating robot, consisting of a non-actuated chaser satellite (from here on, the Chaser) carrying a kinematically redundant robot manipulator. These are shown in Fig. 1.

The task of grasping a target satellite with a free-floating (CHECK) robot was already performed in space in [ETS-VII] and in [Orbital Express], however only for the case of a cooperative Target. When the Target cannot be attitude controlled and does not present visual or structural features to aid its grasping, then it is generally termed non-cooperative. In this case, the accomplishment of the robotic grasping task in autonomous mode presents some substantial challenges. The robot motion is dictated by that of the Target, which is generally unknown. The robot motion also has to be correctly synchronized with that of the Target, in order to meet and grasp some preselected grasping point on it, while satisfying motion constraints, such as workspace limits, kinematic and dynamic singularities, collision avoidance, as well as sensor-driven constraints, such as camera field-of-view boundaries and pixel velocity limits. Furthermore, due to the given free-floating dynamics in play, the effect of an impact during the contact phase can be very detrimental for accomplishing the task, since it can quickly bring the Target out of the range of the robot.

The grasping task of interest has been addressed extensively in the literature, first in the context of feedback control

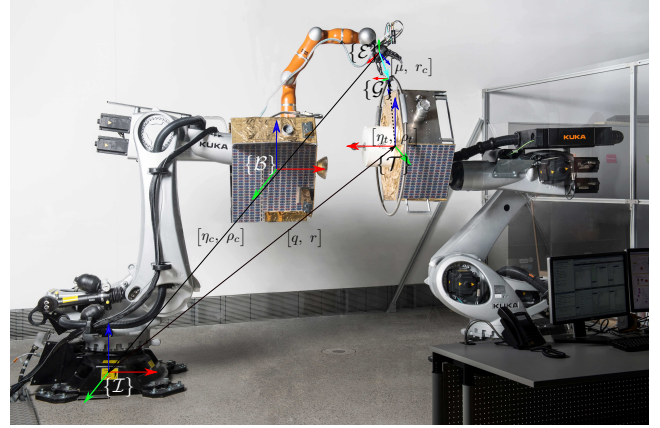


Fig. 1. OOS-SIM experimental facility used to reproduce the gravity-free dynamics of the Chaser (left), carrying a Light-Weight Robot, and the Target (right). A camera is mounted on the gripper of the kinematically redundant manipulator, to allow visual servoing.

and then also in that of optimal control (see Section ???). While in the former the aim is to solve a regulation control problem, often taking advantage of the free-floating dynamics and redundancy of the Chaser, in the latter an open-loop approach is preferred, based on the idea of computing a feasible and optimal trajectory in real-time. Due to the highly constrained task, explained above, the use of a feasible trajectory is recognized to be of great importance.

A gap in the methodology described above, which we want to close here, is that of having both the optimal control and the feedback control elements working together. A feedback controller alone does not provide any guarantee of convergence, given the presence of the constraints, let alone within a limited time window. At the same time, an open-loop approach is not robust to modelling errors and to contingencies, such as an impact. We present here a tracking controller for executing the grasping task of interest, which takes a reference trajectory from a database, generated off-line with a motion planner in simulation and feasible with respect to all relevant constraints, and superimposes on it sensor-based corrections to account for the discrepancy between the simulated and the real world.

The first phase of the task, the approach phase, is executed by means of a pose-based impedance visual servo, bringing the robot end-effector onto the grasping point on the tumbling

Target. It is widely recognized that the robustness of a visual servo is significantly improved against modelling errors when performing tracking rather than regulation [Handbook 2016, Chapter 34, Visual Servoing]. The pose estimates are estimated throughout the motion with a Kalman filter, which is fed with the noisy pose estimates of a model-based visual tracking algorithm. The use of robot impedance control is intended to minimize the detrimental effect of an impact between the robot manipulator and the Target. In the following stabilization phase of the grasping task, in which the Target is already grasped but needs to be stabilized with respect to the Chaser, the reference trajectory provides a final configuration in which to let the system drift with decaying velocity, by virtue of the robot manipulator controller's damping action.

In this paper we present the tracking controller just described and its validation on DLR's OOS-SIM robotic facility, shown in Fig. 1. This facility allows reproducing realistic orbital gravity-free dynamics in three-dimensions through hardware-in-the-loop simulation. The success of the controller requires a judicious interplay between the different elements involved: the motion planner, the pose-based impedance visual servo (including the Kalman filter and the visual tracking) and the free-floating robot impedance controller. Furthermore, the intrinsic uncertainty in the control problem at hand is handled with partial on-line replanning of the reference trajectory. Extensions of the functionality of the OOS-SIM facility to simulate the post-grasping tumbling motion of the satellite stack are also described.

The paper is then structured as follows. In the rest of this section, we present a relevant bibliography and a more detailed problem statement. In Section ??? we provide details of the applied methods, while in Section ??? we present the experimental results and their analysis. In Section ??? we provide our conclusions and views on future work.

#### A. Related work - 0,5 pp

Many approaches for grasping a free-tumbling Target mostly focus on feedback control methods [ ] and momentum control methods [ ]. In [Aghili<sub>TR</sub>2012], the motion planning problem is solved for the approach phase of the grasping task. The planning is supported by a prediction of the Target's motion, achieved through an extended Kalman filter and noisy pose measurements of a laser camera system. The motion prediction occurs before any motion of the robot and the control strategy does not include a continuous visual feedback. An optimization problem is solved partly analytically and partly numerically, to minimize a penalty cost, function of four weighted quantities: travel time, distance, line-of-sight angle of the laser camera and robot joint acceleration. The optimal control for the capturing maneuver is solved in the operational space of the robot manipulator and the robot manipulator kinematics and dynamics are as such not considered. Experiments are conducted on an

experimental facility which reproduces the dynamics of the tumbling Target and of a robot manipulator end-effector with an attitude-controlled base. In [ ] a path planning method is presented for the stabilization phase which follows the grasping. It is assumed that the Chaser is attitude stabilized. As such, an optimal control problem is formulated for the detumbling of the Target to which an external moment is applied, solved analytically for the case of minimum time and zero final velocity.

In [?] an optimal control problem is solved numerically with nonlinear optimization in joint space, addressing the grasping task under the uncertainty of the initial and final positions of the robot end-effector resulting from tracking sensing data. The uncertainty is treated with the Markov Chain Monte Carlo method, which provides an approximation of the expected value of the optimal robot trajectory, in function of a given probability distribution for the uncertainty. The method is applied in simulation to a 2D problem, for a fully attitude controlled robotic system. In [Lampariello<sub>ROS</sub>2013] the motion planning task is solved numerically within nonlinear optimization, with a direct shooting method. The problem is treated in 3D and with inclusion of robot joint position and velocities constraints, as well as the Chaser free-floating dynamics. A look-up table approach is presented with which (close to) globally optimal solutions can be retrieved in real-time for any possible tumbling state of the Target within a predefined range for the angular velocity.

Visual Servoing on ETS-VII [Yoshida] and Orbital Express with markers on Target and inverse kinematics resolution (CHECK and expand). One of the first works which included the use of visual servoing in an experimental setup was [Aghili]. Here, the optimal control described in [ ] was applied on-line under realistic lighting conditions to grasp and stabilize a tumbling target. In [HIT14-timedelayedVS] the grasping task was treated with emphasis on the time delay introduced by the visual servo in the control loop (approximately 500-750ms). The visual servo, which provides pose information between a visual marker on the target and the eye-in-hand camera on the tip of the robot manipulator, was tested on a hardware-in-the-loop robotic facility on ground. The latter consisted of two industrial robots, which emulated the free-floating dynamics of the two satellites, by virtue of a dynamic simulation model (as in [Aghili]).

Visual servoing and position-based impedance control were brought together in [Lippiello], for general tasks in which contact with the environment is foreseen. As such, the aim here was to fuse the visual, joint position and sensory information to improve the accuracy of the estimation of the target object pose. (Phillip: more papers on visual servoing here, for e.g. those cited in Lippiello + others in literature of Handbook?). Model-based methods [?], [?] which exploit robust edge features efficiently, are used in position-based

Fig. 2. The motion of the Target grasping point and of the robot end-effector are shown for the model-based (solid line) and for the true (dotted line) cases.

control. The edge-based method [?] presents a direct and accurate formulation for minimizing the reprojection error from 3D to 2D [?].

### B. Problem statement

In the grasping task of interest we assume that the Target has a known geometry, such that model-based computer vision pose estimation can be used. Its angular rate is limited here to 2 deg/s (due to hardware limitations, the limit for the stabilization phase is set to 1 deg/s). The grasping point on the Target is predefined. The Chaser is not actuated (free-floating) and is initially in the same orbit as that of the Target with zero translational and angular velocities.

The grasping task itself is commonly divided into three phases [IROS13]: an approach phase, in which the robot end-effector is brought above the moving grasping point of the Target; a tracking phase, in which the end-effector follows the grasping point with the same velocity, while homing in onto it and closing the grasp; a stabilization phase, in which the relative velocity between the Chaser and the Target is brought to rest by a suitable control of the robot manipulator.

A feasible trajectory to accomplish this task is provided by a motion planner, first described in [IROS13] and extended here. The motion planner relies on a prediction of the Target motion, which can be accomplished as described in [isairas2005][Aghili][Dobowsky?]. However, in order to complete the task, the tracking controller will initially need to deviate from the reference trajectory, given that the latter is model-based and will differ from the real-world conditions. This fact is shown pictorially in Fig. 2. Note that the gross motion of the motion planner is still maintained, in order to avoid motion constraints such as, for example, a singularity.

Due to the deviation from the reference trajectory in the approach and tracking phases, the reference trajectory for the stabilization phase is adapted online, such that the deviation in joint space is recovered. This favours the fulfillment of joint position related constraints (collisions avoidance, singularity avoidance) throughout it.

## II. METHODS

In this Section we present the methods used to solve the grasping task, to include (CHECK) elements of the motion planning, the visual-servo-based tracking control used in the approach and the tracking phases and the joint-position-based tracking control used in the stabilization phase. The control system architecture is shown in Fig. 3.

Define reference frames: inertia, chaser (?), end-effector, target, grasping point. Diagram needed?

### A. Motion planning and motion synthesizer

The motion planning method adopted in this work is described in some detail in [Lampariello<sub>IROS</sub>2013] - check. We provide here extensions of it, to account for requirements stemming specifically from the visual servo and the joint tracking control and to improve the quality of the solutions presented in [Lampariello<sub>IROS</sub>2013] with regards to the stabilization phase. Check - need to describe method and solutions in some more detail.

#### 1) Motion planning constraints during approach phase:

Add: camera-field of view (constraint on beta check) and end-effector velocity (partially removed velocity jump; define pixel velocity and its constraint); underline outputs: end-effector pose AND robot joint positions PLUS explanation of effect of disturbances (plot as in notepad?); cost function?; look for singularities

In order to feed the motion planner solutions described in [Lampariello<sub>IROS</sub>2013] to the robot controller some adaptations were necessary. The most important were related to motion constraints on the camera-field of view direction, such that the Target remains in view throughout the complete approach phase, as well as on the end-effector velocity (check), such that the pose estimator can perform the tracking in a stable manner (check - expand and/or reformulate):

Equations of e-e direction constraint - analyze again and maybe add new method with cone? since straightforward method has local minima.

The velocity jump between the end of the approach phase and the beginning of the tracking phase was removed, for better performance (check). The latter was also greatly improved by providing the trajectory in form of the relative pose with respect to the Target, ??, but also of the velocity and acceleration (check, also if other). Check for other constraints.

Underline importance of singularities as a motion constraint, since it is not known where they are (esp. in function of load mass, but check Cusumano's) and fact that we need to track grasping point. Methods which use redundancy do not guarantee at all times that grasping point can be tracked at all times (CHECK), since might have deviated path or bring velocity to zero. Furthermore, we don't know if then restofmotion is feasible, since have completely new robot configuration.

2) Motion planning for the stabilization phase: Add: on-line recomputation (see equations in algorithm); cost function LWR mechanical energy plus reason; global search (shows that there are local minima, details of search); other (see notes)

"In this way, by grossly tracking the reference trajectory the feasibility of the complete maneuver is guaranteed. As such, the end time of the stabilization phase need not be minimal, as suggested in [Aghili], since it is sufficient that the system remains in the vicinity of the planned trajectory,

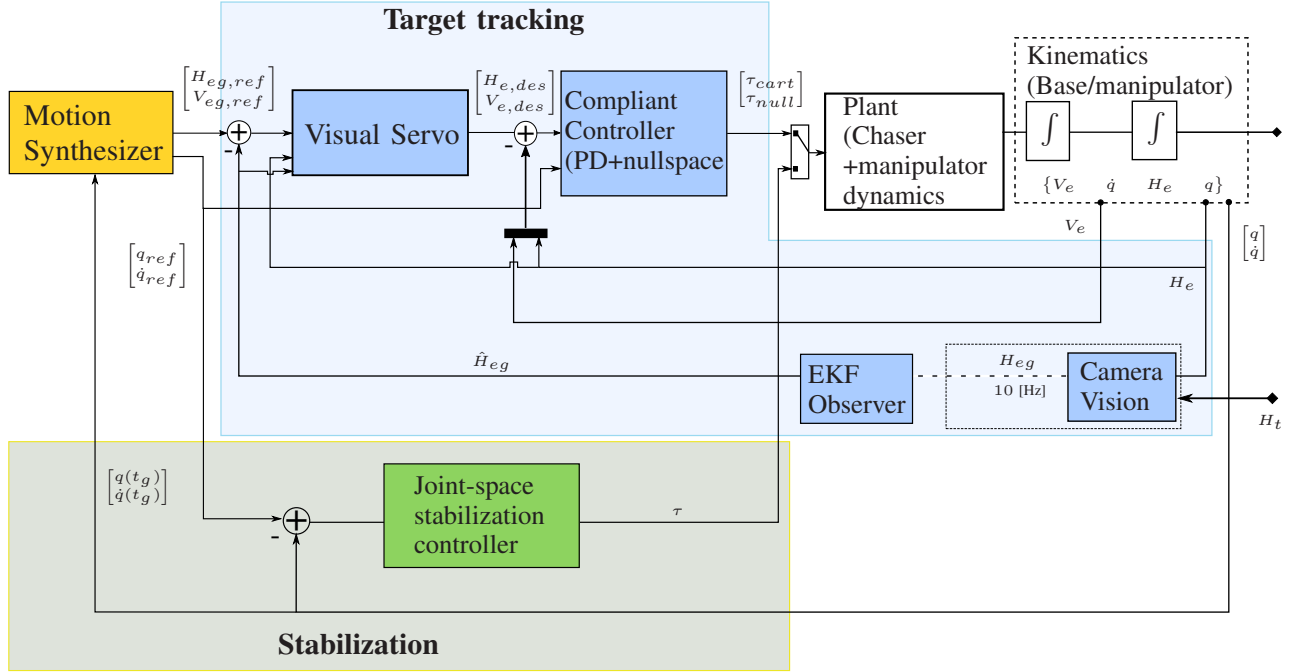


Fig. 3. Control system architecture with...

and may be chosen following a different criterion. Minimum energy maneuvers can be considered as a viable alternative, since, as we will see, they are more robust to modelling errors and visual servo inaccuracies.”

Stress that it is a rigidization, not a stabilization/detumbling), considering compound, best robot motion for chaser to absorb and share target’s momentum, total momentum remains constant.

The optimization problem for the stabilization phase was treated in a similar way as the approach phase. The joint states were parameterized with B-splines and provided the initial conditions in position, velocity and acceleration (check) resulting at the end of the tracking phase. The final conditions on the joint states were only expressed for the joint velocities and accelerations, leaving the joint positions open for the optimizer to be determined, in function of the assigned cost function. Note that this point solves an open issue when only implementing a dissipating control law, to stabilize the compound. In fact, doing so firstly does not give any bound on the final position reached at the end of the motion and as such no guarantee that collisions are avoided. Secondly, due to noise in the system, a purely dissipative control law results in a continuously drifting system (check with Marco and add results later?). The number of parameters was increased, for better convergence performance.

Of notice here is also to realise that the choice of parameterizing the robot joints was favoured with respect to that of parameterizing the end-effector trajectory. This is firstly because the robot control needs joint position commands,

which in our case are given directly from the solution, without having to revert to an inverse kinematics function, to great advantage of the motion synthesizer (see Section ??). The use of an inverse kinematics function is also generally not advisable for the case that a singularity is met. In this case, the inverse of the Jacobian is undefined. However, we note that singularities also provide numerical problems in the presented formulation, due to the fact that even in their vicinity, the joint velocities increase noticeably. The integration of the equations of motion of a free-floating system is very sensitive to large velocities, leading the necessity of an excessively small integrator step size. Check - show example in results?

Results: tau for  $m_{servicer} = inf$  is a lot higher than for  $m_{servicer} = 500$  - show solution and joint taus for both cases? Plus say that total momentum remains constant. Following target trajectory and slowing it down does not take account of chaser inertia. Providing a MBS solution vs Aghili’s single rigid body solution. Show joint curves with zero jerk, for minimizing solar pannel excitation (min time is not ideal for this).

With regards to the cost function, we chose here to minimize the mechanical energy. We propose it as alternative to minimizing the end time given that we track the solution in joint position and as such guarantee the collision avoidance that could arise from any residual relative drift velocity between the two spacecrafts. Although minimizing the mechanical energy requires defining a final time, since the solution would otherwise push the end time to infinity, an arbitrary sensible



value can be chosen by the user, after inspection of the first solutions. It is important to stress that the goal of the motion planner is first to provide a feasible solution. The optimality is then used to make the solutions more robust to the uncertainties. Finally, due to the highly nonlinear nature of the problem (check), a global search is performed, in order to find a (close to) global minimum for a given query. Although we do not address the task of generating a look-up table here, for any tumbling state of interest, we revert the reader to [IROS2013] for further details on this point.

21/12/2017: the chosen cost function for the rigidization is the integral of the product  $\tau * \dot{q}$ . This is best to option to reduce the effort of the LBR! Only drawback is that it does not look nice, i.e. the target rotates toward the chaser (did a global search and could not find any better solutions). The integral of the product  $F_e * v_e$  could be an interesting alternative (given that it implies a solution where the target slows down along its path, without rotating toward the chaser) to minimize the risk of collision, although we can deal with that.

End of current version

Explain motion synthesizer - give details of on-line B-spline with on-line modification function of new robot joint states + Phillip, Marco + see how this can work on board for all required outputs to controller! Then explain how Cartesian trajectory could be modified with motion prediction during approach and how resulting cartesian reference trajectory could be perfectly updated to real motion (relative to the base body). But must choose to give preference to joint position error (which neglects target trajectory change, otherwise don't know where will end up) and possible collision avoidance or to Cartesian error and possible end-effector and joint torque error (show how this can grow, for a given trajectory error!). As such minimizing energy gives a smooth solution and as such a more robust solution to prediction errors, since far from the motion boundaries and not on the edge of them (optimal handling of uncertainties on the off-line generated motion planning solutions). Favoured here avoiding singularities. Furthermore, say that for LBR on OOS-SIM 5 cm error are a lot, but for 3/4 m long arm not.

Say that: The presented method needs to be able to meet strict guarantees on the solution (such as the upper bound on the computation time), for the safety-critical application at hand (software certification processes also need to be considered). As such, all computations involving optimization algorithms have to be performed off-line on ground.

Maybe put all these choices in the results discussion section.

0. motion planning (Roberto): v. say that opt. params for Chaser position are very important for good convergence properties - but add params in approach to improve convergence - to do! vi. say about minimizing joint motion or joint motion in null-space for approach phase - see use of

nullspace term in invkin (see dkin2!!!) - to reduce effect of friction in NS dynamics of real robot - talk to Christian. vii. say that for LBR on OOS-SIM 5 cm error are a lot, but for 3/4 m long arm not. viii. compare min energy solution to solution from  $F_e = K_d * \Delta \dot{x}$  (must implement), for different Chaser/Target mass ratios ix. do global search for min energy or command given  $v_e, \omega_e$  to inv-kin to see solution x. add  $\dot{q}(t_{f_{approach}})$  as parameters to minimize  $\tau(0_{tracking})$  xi. compare joint space to cartesian space stabilization solution approaches x. the problem of extracting the optimal solution from the LUT is not addressed in any more detail here (see IROS 2013)

In pp method? In the proposed method, a motion planner provides a reference trajectory to execute the task described above, details of which can be found in [IROS2013]. Of notice is the fact that the method in [IROS2013] is meant to firstly guarantee the feasibility of the task with respect to all motion constraints, described in Section??. This differs from any of the approaches described in Section???, since there many important constraints are either not treated exhaustively (e.g., joint position and velocity, the latter in view of dynamic singularities, the position of which for a 6 DOF 3D system with n dof and with load X on e-e cannot be predefined to date), implying that the explicit effect of a disturbance or uncertainty on the future evolution of the system is not taken into account, or only added in the cost function as a weighting term (e.g., line-of-sight of end-effector cameras, for which the useful Target features may be lost, with obviously negative consequences), thus not guaranteeing their fulfillment. Here instead, the method based on nonlinear optimization, guarantees the fulfillment of the constraints for the reference trajectory (at the chosen via points, of arbitrary number, sufficient for the task). Due to the highly non-linear nature of the problem, the presented method also provides a (near to) global optimum, for a very wide range of cost functions, for example, minimized for improvement of the robustness of the control method, to model uncertainties and sensor errors, by performing a global search for a given task. The method finally allows to represent the system in question in its full free-floating dynamic behaviour, without the need to reduce the Chaser dynamics to those of a fixed-based robot, for ease of resolution of the related optimal control problem. We will see in Section ??? that the stabilization task is in fact a momentum transfer problem, rather than a detumbling (or passivation?) problem, with useful consequences on the resulting solutions found. The tumbling of the compound after the stabilization is by no means an issue, when realizing that the minimization of the attitude has been solved with simple technological solutions, such as omnidirectional antennas and gymbal joints [DEOS]. The impelling need for robot autonomy for the grasping task was also made evident in [eDeorbit], underlining the need for full autonomy, for which a communication link in the critical

grasping phase is not foreseen. + In the same Figure, the necessity for a motion planner is underlined by showing how this deviates around a robot singularity, rather than going right through it, as a simple regulation controller would do. + make clear statements about singularities: although inv kin methods can avoid them, we can't tell if the motion after them is then feasible anymore, given non-holonomic nature of Chaser dynamics + if cannot avoid them right during tracking, we have a problem + cannot represent them yet. + The uncertainties are quantified and analysed here to some extent, to validate the truthfulness of the assumption. + This last point has required making a decision between prioritizing position related to force related constraints. The internal forces required for the adjustment of the trajectory in the stabilization phase are function of the tracking error in the approach phase, and as such unknown. The alternative would be to recompute the stabilization trajectory online in cartesian space and transfer the unknown onto the final position reached by the robot... + The feasibility (region) is provided by the motion planner, not by the user [Aghili's ball].

#### B. Visual Servo for Approach and Tracking Phases - 1 pp

1. Control Visual Servo Approach (Hrshik, Roberto) -i. describe how to command the planned trajectory to the visual servo (optimization offline on ground, what is done on-line on board?), such that it is grossely followed, both in Cartesian and in joint space, but at the same time corrected by the feedback controller, to account for modelling errors and other uncertainties. 0. The visual servo is described in detail, to include tuning of an inner-loop impedance controller with an outer-loop visual servo, in the approach and tracking phase. i. updated DEOS block diagram (position and impedance control), feedforward term, other ii. inputs from path planner - e-e trajectory, configuration trajectory for null space, other iii. theory for tracking of relative motion iv. theory for tracking of null-space -ask Christian/Alin v. visual servo (computer vision, visual servoing) vi. robot control method for ff robot (Jg) and tracking control; what is maximum allowed impedance of LWR? vii. use of KF with preidentified model parameters, for CV failure (e.g., due to occlusions) viii. The satellite states are assumed to be ideal - check which are needed:  $r_0, v_0, ori_0, omega_0$ , sampling time (3 Hz, 1 kHz), other

1) *Computer Vision for Approach and Tracking Phases:* The visual pose estimation is based on work of [?] which relies on a known object geometry. The algorithm consists of sampling model contours and edge detection, followed by a local optimization of the 3D rigid-body transform. The reprojection error is then minimized between visible model contour and image edges using Levenberg-Marquardt algorithm. The complex motion trajectory (tumbling and an abrupt change of angular velocity) of the target poses difficulty in visual tracking. In order to address this problem, a motion

prediction scheme based on the extended kalman filter is integrated into the local optimization. The prediction relies on a simple kinematic motion model assuming constant frame to frame motion. Under this assumption, the visual tracker is able to cope with relatively higher image motion between two camera frames. Moreover, the short-term prediction scheme helps the visual tracker reduce the search space in order not to trap in potential local optima during minimization of the cost function. The qualitative tracking results are illustrated in Fig. 4, with an exemplar tracked images during approach and tracking phases. Those in red indicate the projection of model contours on to the image edges at the estimated pose. The axes of the coordinate frame of grasping point are indicated in red, green and blue. The overlap of the model contours and image edges shows the successful tracking and pose estimation.

#### C. Joint Tracking Control for Stabilization Phase - 0,5 pp

2. Control Stabilization (Marco, Roberto) i. updated DEOS block diagram (position and impedance control), feedforward term, other ii. inputs from path planner iii. robot control method for ff robot and tracking control iv. add e-e force constraints, e.g. to avoid slipping after grasp v. say that now we can add a proportional term, since we know where to bring the system - not just a damping term. vi. Remind that tracking guarantees feasibility. As such minimum time is useless and relative drift is compensated for by robot. vii. cite Satoko/Lampariello paper for impedance controller as comparison.

### III. EXPERIMENTAL FACILITY - 0.5 PP

i. introduce falcity ii. describe extensions: target motion, post-grasping tumbling motion iii. 4N/1Nm (CHECK) dead-band in Target FTS - removed after grasping iv. End-effector pads to avoid slippage (?)

### IV. RESULTS - 1 PP

Simulation (Roberto): i. analysis of motion planning solution - global search results, cost functions, motion constraints; add a post-processing of the data in log.txt to show the evolution of the optimizer iterations to the solution ii. comparison to Aghili's approach and solutions, analyse mom. + k.e. before and after iii. analyse robustness of solutions to uncertainty iv. provide numbers on field-of-view constraints and graph that meets that v. show exemple with singularity vi. comparison simulation of mission scenario with experimental facility (till contact)

Cost functions: - target k.e.: given nice target motion - robot mech. energy: is much better in comparison to target k.e. in terms of optimal value, but target motion is out-of-plane Compare solutions: - see notes at the end of readme.txt: plot e-e vel and e-e pos. - plot also  $q_{adot}$  to show smoothness from end of tracking to beginning of stabilization - plot  $F_e$  and  $tau_e$  (derive from computation of

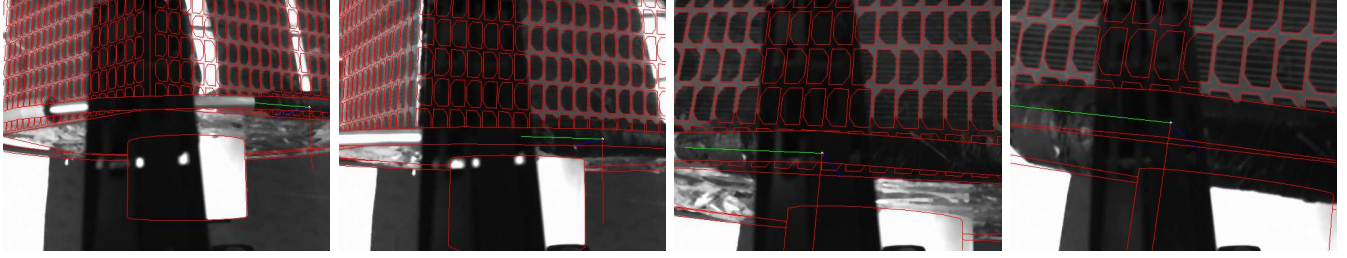


Fig. 4. Exemplar images during visual tracking for approach and tracking phase. The overlay of the model contours and image edges shows the successful tracking and pose estimation. The axes of the coordinate frame of grasping point is indicated in red, green and blue. The target features reduce significantly at very close range because of gripper occlusion (black in the image) and camera field of view.

e-e acceleration? Or from solution of  $\tau = J_T F e$ ?) and cf to  $v_e$  and  $\omega_e$ . Is  $\tau_e$  parallel to  $\omega_e$ ? Should be and see Aghili's analytical solutions as comparison. Optimizer settings: - compare mine with Joos's - compare vels and acc in transition from tracking to stabilization: use vel in *DATA/Output\_control\_invkin\_base\_joints\_vels.dat* - plot(out1(:,1), out1(:,8:14)), but need the values half way along the data, since invkin integrates for twice the length of tracking phase, so do  $n = \text{size}(\text{out1})$ , out1(n/2,8:14) - for tracking phase and *DATA/Results\_joints\_vels\_stabil.dat* - for the stabilization. Show plot:

```
figure(1); plot(out1(1:142,1), out1(1:142,8:14)) hold on;
plot(out2(:,1)+out1(142,1), out2(:,2:8))
```

VS, KF, Controller (Hrshik, Marco): i. tuning details ii. performance details iii. Assumptions: the satellite states are assumed to be ideal or rather in the operational window defined above - check which are needed:  $r_0, v_0, ori_0, \omega_0$ , sampling time (3 Hz, 1 kHz), other. See how to treat this issue in reality (discussion with Alessandro)

Experiments (Roberto, Hrshik, Marco): i. experimental facility description - add changes applied for Institutsueberpruefung: post-capture motion as a momentum conservation task, 3D target motion, other ii. examples with different tumbling target states - success of tracking and of satisfying motion constraints, cost function in experiments vs in simulation iii. null-space motion tracking iv. end-effector force slip limit satisfaction iii. comparison to regulation approach? Show that less robust and can become faulty due to motion constraints iv. solution for CV frame loss, i.e. performance of KF on-line v. performance analysis with modelling/prediction error vi. show open-loop motion with impact on target vii. show singularity with N45 (or N30) and inertia servicer divided by 10 - perhaps seen on OOS-SIM

#### V. CONCLUSION - 0,25 PP

- Shown feasibility of method (pp, VT for approach with CV and KF, tracking, grasp, stabilization), with experimental results on OOS-SIM.

- rivedi tutti commenti in Aghili papers!
- describe complete story (isairas 2005, pp iros2013 and this), where here we focus on the third part. We here make

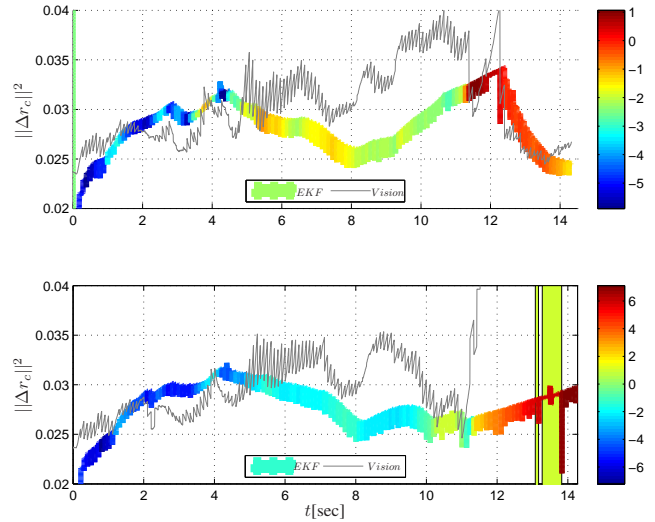


Fig. 5. Comparison of direct-Vision measurements with EKF, based on the norm,  $\|\Delta r_c\|^2$ . As  $\|r_c\| \rightarrow 0$ , the statistical measure of fitness,  $\chi^2 \rightarrow \infty$  eventually leading to pose estimation failures due to degenerate observability

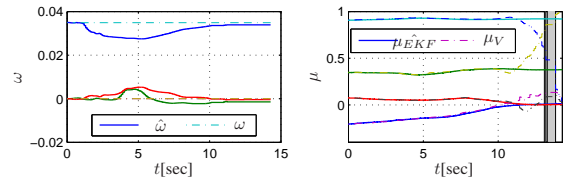


Fig. 6. a) Target state estimation ( $\omega$ ) in EKF for tracking control. b) Divergence of Computer vision's orientation estimate towards end of maneuver

the motion planning (of the type in IROS2013) useful for control purposes, through the use of tracking control.

- since pp without feedback tracking control is no use for control purposes, we show here how the pp in [IROS2013] can be used exactly for this goal.

- See Balandat's statement (see above) + one on LUT idea. Therefore, we strongly believe that use of offline generated solutions retrieved on-line is the future, especially for complex tasks like grasping and stabilization in the presence of



constraints (communication, other).

- still to do is validation with orbital lighting conditions.
- pp + VT for grasping is also new (said already). The stabilization task with a reference trajectory is new, with respect to the methods existing in the literature.

- future work: include realistic illumination conditions, method to provide ref traj in useful time for complete taskspace.

- Said motivation for pp in Berlin talk, specific DEOS TN?  
"Since we also want to be able to deal with a contingency case, for which an undesired impact between the robot and the Target may occur (CHECK need to demonstrate in experiments?), the feedback control method is based on impedance control. This allows to handle the case of an impact robustly, by suitably tuning the impedance []. Furthermore, the possibility of losing the Target after the impact is further greatly reduced by the visual servo."

## VI. VIDEOS

1. simulation - bernhard 2. facility

@proceedingsDrummond2002, Author = T. Drummond and R. Cipolla, title= Real-time visual tracking of complex structures, booktitle= IEEE Trans. Pattern Analysis and Machine Intelligence, pages = 932–946, year = 2002

@proceedingsComport2004, Author = A.I. Comport, E. Marchand, F. Chaumette, title= Robust model-based tracking for robot vision, booktitle= Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, volume =1, pages = 692–697, year = 2004

@proceedingsComport2005, Author = A.I. Comport, D. Kragic, . Marchand, F. Chaumette, title= Robust real-time visual tracking: comparison, theoretical analysis and performance evaluation, booktitle=Proceedings of the IEEE International Conference on Robotics and Automation, volume = 1, pages = 2841–2846, year = 2005

@articleOumer2015, title = Vision-based localization for on-orbit servicing of a partially cooperative satellite, author = Nassir W. Oumer and Giorgio Panin and Quirin Milbauer and Anastasia Tseneklidou, journal = Acta Astronautica, volume = 117, pages = 19–37, year = 2015

@phdthesisOumerPhdThesis, author = Nassir W. Oumer, title = Visual Tracking and Motion Estimation for an On-orbit Servicing of a Satellite, booktitle=Phd Thesis, Address = University of Osnabrück, year = 2016

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The preferred spelling of the word acknowledgment in America is without an e after the g. Avoid the stilted expression, One of us (R. B. G.) thanks . . . Instead, try R. B. G. thanks. Put sponsor acknowledgments in the unnumbered footnote on the first page.

References are important to the reader; therefore, each citation must be complete and correct. If at all possible, references should be commonly available publications.

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