Grasping Strategies and Dynamic Aspects in Satellite Capturing by Robotic Manipulator

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ABSTRACT

Since several years the interest in offering satellite services for maintenance and repair of malfunctioned satellites is strongly increasing. Automation and robotics (A&R) will become one of the most attractive areas for such applications. Currently, a very typical and actual application is dedicated to the rescue of a defect satellite (Rosat) in low earth orbit by means of a servicing satellite based manipulator. This paper presents a new manipulator design approach. It focuses on the development of grasping strategies in conjunction with the goal to reduce dynamic loads in the robotic manipulator.

INTRODUCTION

Due to their great adaptability to extreme outer space conditions and due to their enhanced flexibility to fulfil successfully a large variety of complex tasks, the use of robotic manipulators is becoming more and more important. The necessary operational modes for such unmanned missions, autonomous or teleoperating, have already been demonstrated [1]. Recent market analyses indicate a growth market for the next years for servicing satellites for maintenance (e.g. refuelling satellites in geostationary orbit), repair and the controlled de-orbiting of satellites. The current end-of-lifetime German Roentgen Satellite Rosat (launched in 1991) may serve as a candidate to demonstrate the performance of these novel in-orbit technologies. The main tasks of this mission are to grasp Rosat, perform a tight connection between the two satellites, and finally realize a controlled descending of both and crash in uninhabited area, preferably the Pacific Ocean [2]. The combined system consisting of two satellites that are connected by a manipulator with elastic joints represents a very delicate dynamical system, which has to be carefully investigated in order to guarantee for mission success. The dynamic studies are oriented w.r.t. the different operational phases: arm deployment, final approach with minimum relative velocity for contact, grasping of an elastic slender boom on Rosat side, performing close contact via manipulator action, pushing of the combined system for controlled descent. What makes the entire manoeuvres such dynamically critical is primarily originating from a) the use of a new generation of very light-weight robotic components (joints and arm structure), b) the non-cooperative target satellite (grasping of a slender boom), and c) the choice among various capturing strategies. These dynamic aspects are carefully considered in order to minimize both, the strong vibrational behavior of the combined satellite system, and the mechanical stresses in the slender boom and the robotic joints and arm structure, and consequently, to find the optimal capturing strategy.

MOTIVATION

Future space missions will require highly specialised manipulators to fulfil their challenging tasks. To shorten the development time and costs, a general procedure is necessary to develop operations strategies and design a suitable manipulator in a fast and flexible way for different applications. Therefore concurrent engineering with extensive simulation at an early stage of development is inevitable. Furthermore new aspects like microgravity and the free-floating condition cannot, or otherwise at very high expenses, be fully examined on ground. For the Rosat de-orbiting such an application is developed for the very first time and future missions will strongly benefit from the results. One of the major problems of these missions is, that the unknown actual movement behaviour of the target satellite requires an on-site maneuver determination and therefore a highly flexible operations planning (Fig. 1). Each manoeuvre determinates the starting configuration for the next operation and therefore strongly affects the overall strategy. A scenario with the corresponding strategy requires a specific dexterity and influences the manipulator design. Changes in the manipulator design will influence the other operations again. The different operational scenarios have to be evaluated well in advance. Only a virtual mock-up allows considering these interactions in an easy way.
THE ROSAT DE-ORBITING STRATEGY

Since its mission termination in 1999 the German scientific satellite Rosat (Roentgen Satellite, Fig. 2) is continuously declining in orbit. An uncontrolled crash is expected for 2007. To ensure controlled crash in uninhabited area of the uncontrollable Rosat, a rescue satellite (Fig. 3) mission has been studied that has to grasp Rosat, perform a tight connection between the two satellites and finally realize a controlled descending of both [2,3].

During the first stage of the mission the servicing satellite has to determinate a suitable grasping point, approach the target, adjust the spin rate and deploy the manipulator. It has been identified before, that the best way to grasp the robotically non-cooperative Rosat, is given by the slender antenna boom. An unfavorable movement behavior of the Rosat may require choosing one of the less accessible grasping points. Care has to be taken in order not to overstress these mechanical smart parts. The next step is to grasp Rosat free of bumps. The satellite approach, manipulator deployment and grasping operation, while kinematically challenging, cause only minor mechanical stresses. Therefore, this paper will focus on the coupled system.

The de-orbiting operation requires a coarse alignment of the thrust vector through the center of mass of the coupled system. To move the servicing satellite from the grasping configuration to one of the two possible de-orbiting configurations depicted in Fig. 4, a corresponding alignment operation has to be performed. Finally, a controlled deceleration of the coupled system initiates the de-orbiting. The grasping operation as well as the de-orbiting operation can be performed with active or inactive Attitude and Orbit Control System (AOCS). For the delicate free-floating conditions (inactive AOCS) any movement of the manipulator will result in a movement of the entire system, which makes an absolute path planning more complex and probably decreases the accuracy. The grasping operation should therefore be performed with active AOCS whereas for the alignment operation the free-floating condition should be preferred. This operation requires a movement of the rescue satellite relative to Rosat. Therefore the movement of the coupled system will not affect the accuracy. But for free-floating conditions the loads will decrease dramatically and less propellant is needed. Considering the AOCS is used to control the servicing satellites attitude, the heavy Rosat has to be moved towards the servicing satellite. The loads for free-floating conditions are more comparable to those for fixing the much heavier Rosat and moving the servicing satellites. Fixing the Rosat increases the system stiffness and therefore the mechanical stresses increase, when compared to the real free-floating conditions.
MANIPULATOR

The manipulator design focuses on the most critical task, the grasping operation. Redundant manipulators are able to enhance skill and flexibility of the entire robotic system, and hence increase the operational use in order to obtain the maximum benefit of the robotic workspace. Moreover, avoiding collision with obstacles, and the avoidance of and passing through singularities are two more major aspects that make the use of redundancy of manipulators for space applications very preferable. Therefore, from the beginning, DLR’s robots have been kinematically redundant (7-degrees of freedom (DOF), or even more) [4].

To reduce development costs and time and to reduce weight, the overall robot construction makes use of DLR’s novel light-weight robotic components. The joint types and links are all of similar size and performance. The roll, pitch and yaw joints then can be assembled easily for any kind of kinematic configuration. Also, the length of the arm structure, limited by the launch configuration, can be selected accordingly. For the pitch-yaw-roll-pitch configuration with roll-pitch-roll wrist, depicted in Fig. 5, the maximum work space (3m) and dexterity is achieved with a total mass of just 19 kg (Fig. 5).

TRAJECTORY PLANNING

The redundant 7 degrees of freedom light-weight manipulator enables variable manipulator configurations for a given trajectory. Additionally, the redundancy can be favorably used to force the manipulator to stay near a reference configuration, usually the starting configuration. Moreover, it could also be used to optimize another cost function e.g. to minimize the joint accelerations [5]. The Inverse Kinematics Algorithm cannot straightforwardly calculate the joint angles $q_E$ for the desired final Tool Center Point (TCP) Position $B_E$. Therefore intermediate points $B_i$ (Fig. 6), within
the neighborhood of the actual position, have to be used to solve for the final configuration. Furthermore for the free-floating condition the system possesses non-holonomic properties. Thus the final state of the system is dependent upon the systems kinetics and the path taken to reach it [6]. For a fixed base the intermediate configurations do not have to be used. The trajectory between two configurations depends on the robot control strategy and passes only through the intermediate configurations used for the control strategy. Next, the trajectory between the manipulator configurations has to be calculated. This can be done on joint level or TCP level by means of the velocity and acceleration. A control strategy on TCP level (Fig. 7) is dedicated to the alignment operation, as the loads applied to the system mainly depend on the acceleration of the heavy Payload (Rosat).

![Fig. 6. Path planning: intermediate points (left), manipulator configurations for the intermediate points (middle) and trajectory (right)](image)

**Fig. 6. Path planning: intermediate points (left), manipulator configurations for the intermediate points (middle) and trajectory (right)**

**Fig. 7. Robot control strategies: TCP control (left) or joint control (right)**

**KINETICS**

For a fixed base the absolute velocity and acceleration of link \( n \) depends only on the preceding joints and not on the kinetics of the system. Thus, starting at the base, the kinematics of each link can be calculated straightforwardly (Fig. 8). With the kinematics and starting at the last link (link and payload), considering no unknown external forces, the stress resultants for each link and thus the systems kinetics, can be calculated.

![Fig. 8. Calculation of kinematics and kinetics for fixed base](image)
For free-floating conditions, the base is able to move and the additional 6 DOF of the base link have to be considered. The kinematics of the manipulator, respectively the motion behaviour of the base link, depends on the systems kinetics.

To calculate the motion behaviour of an n-DOF-manipulator, a complex equation system with \( n+6 \) generalized coordinates and 6 kinetic boundary conditions has to be solved [6]. Here a different approach is followed. The movement behaviour can be subdivided into a relative part, representing the influence of the movement of the manipulator relative to the base link, and into an absolute part, representing the influence of the acceleration of the first link.

The absolute velocity of point P (Fig. 9) is given by
\[
v = \frac{dr}{dt} = \frac{dr_0}{dt} + \omega \times r + \frac{d\omega}{dt} \times r = v_0 + \omega \times r + \frac{d\omega}{dt} \times r
\]
and the absolute acceleration of point P by
\[
a = \frac{d^2r}{dt^2} = \frac{d^2r_0}{dt^2} + \frac{d^2\omega}{dt^2} \times r + \frac{d\omega}{dt} \times \frac{d\omega}{dt} \times r + \omega \times \frac{d\omega}{dt} \times r.
\]

Assuming rigid body motions and rotational joints \( \left( \frac{d\mathbf{r}'}{dt} = 0 \right) \), the absolute velocity of the \((n+1)^{th}\) joint is
\[
v_{n+1} = v_n + \omega_n \times r_n = v_n + \left( \omega_n + \sum_{i=1}^{n} \dot{q}_i \right) \times r_n.
\]
where \( \omega_n = \omega_{n-1} + \dot{q}_n = \omega_0 + \sum_{i=1}^{n} \dot{q}_i \). The absolute acceleration of the \((n+1)^{th}\) joint can be calculated as
\[
a_{n+1} = a_n + \frac{d\omega_n}{dt} \times r_n + \omega_n \times (\omega_n \times r_n).
\]
By recursion (3) takes on the form
\[
v_{n+1} = v_n + \left( \omega_n + \sum_{i=1}^{n} \dot{q}_i \right) \times r_n = v_n + \omega_n \times \sum_{i=1}^{n} \dot{r}_i + \sum_{i=1}^{n} \left( \omega_0 + \sum_{j=1}^{i-1} \dot{q}_j \right) \times \left( \omega_0 + \sum_{j=1}^{i-1} \dot{q}_j \right) \times r_i.
\]
and (4) the form
\[
a_{n+1} = a_0 + \omega_0 \times \sum_{i=0}^{n} \dot{r}_i + \omega_0 \times (\omega_0 \times r_0) + \sum_{i=1}^{n} \left( \omega_0 + \sum_{j=1}^{i} \dot{q}_j \right) \times \left( \omega_0 + \sum_{j=1}^{i} \dot{q}_j \right) \times r_i.
\]
where \( \frac{d\omega_n}{dt} = \dot{\omega}_n = \dot{\omega}_{n-1} + \dot{\dot{q}}_n = \dot{\omega}_0 + \sum_{i=1}^{n} \dot{q}_i \). Assuming zero gravity, the equilibrium of forces for link n (Fig. 10) leads to
\[
F_n = m_n a_{cn} + F_{n-1}
\]
By recursion and with (6) the latter equation takes on the form
\[
F_n = \sum_{i=n}^{k} \left( m_i a_{ci} \right) = \sum_{i=n}^{k} \left[ m_i \left( a_0 + \omega_0 \times r_{ci} + f(\omega_0, \dot{q}, \ddot{q}) \right) \right].
\]
For the first link and with the definition of the center of gravity

\[ r_{C,Rob} = \left( \sum_{i=0}^{k} r_{Cl,m_i} \right) \left( \sum_{i=0}^{k} m_i \right) \]  

(9)

(8) is expressed as

\[ \mathbf{F}_n = \sum_{i=0}^{k} m_i \left( \mathbf{a}_i + \dot{\mathbf{a}}_i \times \sum_{j=0}^{i} r_{F,Rob} + \mathbf{f} (\mathbf{\omega}_j \times \mathbf{q}, \dot{\mathbf{q}}) \right) = m_{Rob} \left( \mathbf{a}_n + \dot{\mathbf{a}}_n \times r_{C,Rob} \right) + \mathbf{f} (\mathbf{\omega}_n \times \mathbf{q}, \dot{\mathbf{q}}) = \mathbf{F}_{Rel} + \mathbf{F}_{Rob} (\mathbf{\omega}_n \times \mathbf{q}, \dot{\mathbf{q}}) = 0 , \]  

(10)

where \( m_{Rob} = \sum_{i=0}^{k} m_i \). According to (10) the force applied to the base can be divided into two parts, where \( \mathbf{F}_{Rel} \) represents the force caused by the movement of the manipulator relative to the base, and \( \mathbf{F}_{Rob} \) represents the rigid body motion of the entire system. The equilibrium of torques for link \( n \) leads to

\[ \mathbf{T}_n = m_n \left( r_{C,n} \times \mathbf{a}_n \right) + \mathbf{J}_{Inp,n} \dot{\mathbf{a}}_n + \mathbf{J}_{Inp,n} \times \mathbf{\omega}_n \times \mathbf{a}_n + r_n \times \mathbf{F}_{n+1} + \mathbf{T}_{n+1} , \]  

(11)

where \( \mathbf{J}_{Inp} \) is the tensor of inertia of link \( n \) w.r.t. input marker \( n \).

Thus one can obtain for the torque applied to the base

\[ \mathbf{T}_0 = \sum_{i=0}^{k} m_i \left( r_{C,i} \times \mathbf{a}_i \right) + \mathbf{J}_{Inp,i} \dot{\mathbf{a}}_i + \mathbf{J}_{Inp,i} \times \mathbf{\omega}_i \times \mathbf{a}_i + \sum_{j=0}^{i} r_{F,Rob} \times \mathbf{r}_{C,Rob} \]  

\[ + \mathbf{f} (\mathbf{\omega}_j \times \mathbf{q}, \dot{\mathbf{q}}) = \mathbf{T}_{Rob} + \mathbf{T}_{Rel} (\mathbf{\omega}_n \times \mathbf{q}, \dot{\mathbf{q}}) = 0 , \]  

(12)

where \( \mathbf{J}_{Rob} \) is the tensor of inertia and \( r_{C,Rob} \) the center of gravity of the manipulator w.r.t. the base. Corresponding to the force applied to the base, the torque can also be separated in a relative part and a rigid body motion of the entire system. The relative loads can be calculated straightforwardly by adapting the algorithm for a fixed base to a base with constant velocity. From (10) and (12) one can now readily solve for the acceleration of the base and therefore for the system behavior.

**SIMULATION RESULTS**

**Alignment Operation**

The simulation environment is based on a combination of the standard software tool Robcad and special software tools, developed at DLR, for the Inverse Kinematics and Kinetics.

For safety reasons the maneuver respectively the path planning focuses on collision check rather than on dynamic aspects. For the optimised path a trajectory has to be evaluated, which allows performing each operation within one single contact time zone (visibility from earth) and does not over stressing the manipulator. The manipulator design and the operation planning have to consider the worst case. Therefore the alignment operation with active AOCS and joint control has to be evaluated. For this dynamically most critical task the drive torque (nominal torque: 80 Nm), the power (nominal power: 10 W) and the forces and torques exerted to the manipulator and the slender boom (maximum allowed combined stress: 100 N/mm²) have to be carefully investigated. Though for each robotic joint the maximum velocity is 187 °/s and the maximum acceleration 1145 °/s², for space applications manipulators are commonly operated at low velocity and acceleration. Due to the heavy payload (Rosat: 2500 kg) the manipulator has to be operated at very low joint accelerations and the angular acceleration of each joint has to be chosen carefully according to the particular trajectory and grasping distance. For this investigations, the joint accelerations of the first three links are set to 0.1 °/s², for the fourth joint to 0.2 °/s² and for the last three joints to 0.3 °/s². For the investigations the optimized trajectories for the grasping and de-orbiting configurations depicted in Fig. 4 are considered. The joint angles for the corresponding alignment operations are depicted in Fig. 11. To analyze the influence of the grasping point, the position of the grasping point on the boom is varied. Strictly speaking, the considered trajectories hold only for the grasping distance (1.6 m from Rosat) of Fig. 4. For a different grasping point the trajectories would have to be adapted slightly. For both alignment operations, i.e. axial and lateral, the maximum joint accelerations are limited by the maximum allowed drive torque: for the axial de-orbiting configuration this is the first joint and for the lateral de-orbiting configuration this is the third joint (Fig. 12). For both alignment operations the combined stress and the power are well within the limits (Fig. 13).
The vibrational behaviour of the coupled system can only be performed by means of the attitude control system of the servicing satellite. Thus, the eigenfrequencies of the coupled system have to be considered for the attitude control system design as well. Considering the satellites as rigid bodies and the connecting antenna boom as a massless beam (Fig. 14), following the Bernoulli-Euler beam theory, one obtains a system of four coupled linear equations for the four degrees of freedom given by $z_1$, $\phi_1$, $z_2$, and $\phi_2$. The four eigenfrequencies of the coupled system are given by
whereas two of them represent rigid body motions and the other two non-zero ones are calculated by letting the big bracket of (13) being zero. The dominant eigenfrequencies are below 15 Hz and therefore have to be regarded for AOCS design (Fig. 15).

\[
0=\omega^4 + \frac{12EI}{I^3} \left( (M_1+M_2)I_1 + M_1M_2^2 \left( \frac{1}{3} + \frac{S_2}{I} \left( 1 + \frac{S_1}{I} \right) \right) + I_1 \left( \frac{1}{3} + \frac{S_1}{I} \left( 1 + \frac{S_1}{I} \right) \right) \right)
\]

\[
+ \frac{12EI^2}{I^5} \left( (M_1+M_2)(I_1+I_2) + M_1M_2^2 \left( 1 + \frac{S_1}{I} + \frac{S_2}{I} \right) \right)
\]

\[ (13) \]

CONCLUSIONS AND FURTHER ACTIVITIES

For the efficient design of the robotic manipulator for grasping and de-orbiting operations, DLR's new developments in advanced light-weight technology and kinematic redundancy has been favourably utilized. Furthermore, it has been shown by inverse kinetics problem solving for the selected grasping and de-orbiting strategies, that the mechanical loads on the robotic joints and the mechanical stresses on the antenna boom are not exceeded. The underlying investigations were carried out for the specific mission scenario of the German satellite Rosat in low earth orbit. However, the methods presented for kinematic and kinetic load studies are expected to hold true also for future scenarios where satellite capturing by means of a servicer based manipulator is of primary interest. Our approach is seen to be of dominant importance in order to guarantee for mission success.

Further activities are directed towards the on-site mission planning for optimized grasping and de-orbiting strategies. Therefore investigations for the free-floating case have to be carried out in more detail.

REFERENCES