Autonomous Grasping with a 3-DOF Gripper for Space Activities

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Abstract

In the space context, because of the technical difficulties, dangerous environment, high cost of communications and of human presence and so on, the development of devices for autonomous or semi-autonomous operations is a key point for present and future researches. In this scenario, an important role will be played by robotics systems, able to interact with and to operate in a possibly unstructured environment.

Aim of this work is to show how a robotic arm/gripper system and a vision system can be properly integrated in order to achieve the capability to autonomously perform the grasp of unknown objects. The gripper (currently mounted on a standard industrial manipulator) has been purposely designed for space applications. As a matter of fact, its kinematic configuration (3 one-dof fingers) and its sensorial equipment (including position, force and proximity sensors), improve the dexterity of this device if compared to more classical 2-jaw devices, usually used in space. In particular, the features of the proposed device (besides its wide workspace and the possibility to grasp objects with irregular shapes and/or non well positioned within its workspace) make it particularly suitable to deal with free-floating objects in absence of gravity.

Keywords: Robotic Gripper, Space Robotics, Floating Objects, Vision System, Autonomous Grasp.

1 Introduction

In the last decade, in order to replace the crew in the execution of some repetitive and time consuming tasks, robotic arms have been designed and already tested in space. With respect to end-effectors, these manipulators were equipped with simple grippers with very limited grasp and manipulation capabilities, while the current researches for advanced application on earth addresses the development of dexterous hands with anthropomorphic structure and very high complexity. In order to reduce the gap between these opposite trends, we have proposed an intermediate solution, i.e. a 3-fingered gripper [1, 2, 3]. Main features of this end-effector are a quite simple mechanical structure, where the 3 fingers are able to move radially towards the center of the device. The mechanical design allows a very wide workspace (with respect to the physical dimension of the gripper) and the capability of firmly grasping object with different shapes and sizes. In order to enhance its skills, the device is equipped with a high-level sensor equipment.

The gripper is currently installed on a robotic arm, the Comau SMART-3S (an anthropomorphic manipulator with 6 dof) and a video-camera has been added to the set of proprioceptive sensors. The aim of this final stage of the project is of testing the capabilities of the gripper as an element of a more complex system. In particular, an automatic procedure to approach and grasp an object has been implemented. This procedure, based on the images obtained by the camera, first selects the best points for the grasp (i.e. determines the best grasp configuration for the given object), then controls the gripper-arm system in order to get the desired configuration.
The overall system

Besides the gripper, which is the main subject of the present research project, the robotic setup includes other important components (schematically shown in Fig. 1), such as the carrying robot arm and the vision system.

The robotic gripper

The gripper, shown in Fig. 2.a, has a simple and modular structure, with three one-dof fingers disposed radially, in a symmetric configuration, whose distal phalange can move along a linear trajectory, see Fig. 3.b. Despite its simplicity, this kinematic configuration allows to firmly grasp objects with irregular shapes and with a rather wide range of dimensions.

The sensory system of the gripper has been designed taking into account both the motion of the fingers and the approach and interaction phases with the grasped object. In particular, each finger is equipped with a Hall effect position sensor, a proximity sensor and a miniaturized force/torque sensor, as shown in Fig. 3.a. The proximity sensor (based on a simple light emitter-receiver) measures the distance of each finger from the object surface and allows to plan the approach motion in order to get synchronous contacts while the force-torque sensor (which can detect the interaction forces, by measuring the deformation on the fingertip structure by means of the classical strain gauge technology) can be used for the control of grasping forces once contacts have been applied. Note that, being capable of detecting not only the intensity of contact force components but also the position of the contact centroid on the external surface of the finger, the intrinsic tactile sensor can efficiently recognize actual contact conditions, including incipient sliding [4].
The presented robotic end-effector has been designed considering its hypothetical installation on the SPIDER arm by ASI (Italian Space Agency), [5], but a redesign of the gripper itself has been performed in order to reduce the total size and make this new device compatible with PaT, the Payload Tutor, also proposed by ASI [6]. This system aims to substitute the astronauts in periodical operations with a semi-autonomous robotic device, for instance to deal with the experiments performed in space. These operations may include simple manipulation tasks of complex-shape “non-technical” objects, freely floating within their allowed space. The end-effector for the PaT manipulator needs therefore compactness, simplicity and reduced weight as well as capability of operation even on irregular floating objects.

**The arm and vision system**

The gripper has been mounted as end-effector on a Comau SMART 3-S robot arm, see Fig. 2.b. This is an industrial 6 degrees of freedom robot anthropomorphic manipulator with a non-spherical wrist. The robot is equipped with the standard controller C3G-9000, which drives the manipulator according the user commands. In our setup this controller is open, that is it has been connected, by means of an high-speed bus, to a PC which can perform the real time control, using the controller as a simple interface towards the robot (in order to acquire the data from the encoders and drive the motors). Moreover a camera, whose images are acquired by means of a frame grabber, has been installed on the wrist of the robot arm.

3 Control architecture

The control of the arm/gripper system is based on 3 main elements: 2 standard PCs and a general purpose DSP (TMS320C32) board, as shown in Fig. 4. This last board is devoted to the control of the robotic gripper and it has been connected to the motor drives and to an input board, purposely designed in order to multiplex the relatively high number of signals (30) coming from the sensors. The DSP is hosted on a PC, which provides an high-level user interface and allows the communication with the other components of the robotic setup. In particular this PC, equipped with a real-time version of Linux Os (RTAI-Linux [7]), is the heart of the whole system. As a matter of fact, the kernel real-time running on it performs the position control of the robot arm, while a user space application (and therefore not real time) carries out the supervision of the system based on the information coming from the gripper control, the arm control, the vision system and according to the desired tasks [8].

Finally, the aim of the second PC is to process the images and to extract the features (e.g. position of the target object) necessary to drive the manipulator. Note that the functions performed by this PC can easily be hosted also on the first personal computer.
Control of the gripper

In order to cope with the main problems of the space environment (e.g. the lack of gravity) and exploit the structural features of the gripper a logic-based switching control has been designed. As a matter of fact, the different tasks are performed by the gripper according to a sequence of the following main controllers:

- position control;
- proximity control;
- stiffness control.

The position control of each finger is based on a classical PI regulator, as depicted in Fig. 5. At this level, a difficulty has been the compensation of nonlinearities caused by the actuation system, in particular a relevant (and non constant) dead zone and the nonlinear characteristic of the Hall effect position sensors. The same structure has been exploited to accomplish the proximity control of the finger (by simply switching the feedback signal from the position sensor to the proximity one), and in order to guarantee a smooth behavior of the finger a proper trajectory generation has been implemented. In this modality, it is possible to approach the fingertip to the object surface up to the desired distance and keep that constant, thus avoiding undesired interactions.

Instead, when an interaction with the environment (usually the grasped object) is desired, the force exerted by the fingers can be regulated by means of a stiffness control, which in steady state assures an applied force...
proportional to the displacement from the desired position ($x_d$):

$$F = K_e (x - x_d)$$

In this way each finger behaves like a programmable spring, whose stiffness $K_e$ can be modified according to the desired task.

In Fig. 6 it is shown how a sequence of primitive controllers has been arranged in order to get a safe execution of a grasp task, that is the most critical operation the gripper must perform. First, the fingers approach the object within the gripper workspace by means of the position control, then when a distance $p^*$ has been detected, the proximity control is activated in order to reach and maintain the desired distance $p$ from the object surface. Only when all the fingers are at distance $p$ (sufficiently small) they are synchronously closed on the object. In this way it is possible to avoid undesired contacts with the object, which can cause its loss due to the lack of gravity, and assure a synchronous grasp of irregular or moving object. Finally when the forces applied by fingers become appreciable the stiffness control drives the motors in order to get the desired force values.

Control of the arm and supervision

The Comau robot arm must lead the gripper in the right position in order to grasp the object. For this purpose it is used under a cartesian position control which allows to move the end-effector according to user commands. In this specific application an automatic grasp procedure has been implemented based on the feedback of the camera. A supervision system uses the information extracted from the images to compute the distance from the target and plan the proper approach phase. Obviously, because we are not using a stereo-camera, 2 images from 2 different points of view (whose relative positions are known) are necessary. Moreover the camera is used to implement a classical algorithm, based on visual feedback, of the kind look-and-move [9]: from the images the position set-points for the manipulator are constructed in order to bring the gravity center of the target into the center of the image.

4 Choice of the grasp configuration

In order to deal with objects with variable and unknown shapes, a grasp synthesis algorithm has been implemented. The main theoretical foundation of this procedure is the concept of immobility, that is the lack of any freedom for finite movements of the immobilized object. In fact, considering a possible use of the robotic gripper in a space environment, the classical optimization processes of grasp points choice, appear not completely effective or not suitable. Aim of these algorithms is to collocate the contact points on the surface of target objects in order to maximize the external wrenches, which can be resisted by the fingertips’ forces [10, 11]. But it is worth to notice that, due the lack of gravity, the magnitude of external forces in the space environment are usually quite small. Instead the most critical problem in this context is the stability [12] of the grasp; as a matter of fact a small unbalanced force or a positioning error can produce the loss of the object. Therefore in this case it is necessary to find a configuration as insensitive as possible to this kind of disturbances. Moreover,
also the constraints imposed by the mechanical structure of the gripper must be considered. In fact the fingers have a single degree of freedom and can behave as simple linear springs moving along the radial direction. The implemented procedure considers 2D grasps, therefore it is suitable for relatively flat objects, or that can be treated as an extrusion of their projected silhouettes. This hypothesis is not too limiting but appears consistent with the mechanical structure of the gripper, which (considering its three parallel fingers) results particularly suitable to deal with this kind of objects.

The grasp synthesis algorithm is based on several steps aiming to identify the best triplet of contact points, [13].

**Step 1: Parameterization of object contour**
The presented algorithm relies on a image processing procedure and does not require any model of the object. Based on images obtained by the camera, the object shape is extracted (according to standard algorithms) and parameterized by means of circular arcs. Of each arc, the curvature (obviously infinite if straight lines are considered) and the normal vector (in the middle point) are computed.

**Step 2: Equilibrium test**
This stage aims at selecting all the triplets of arcs, which might be possible candidates for the grasp. In order to hold the object, a necessary condition is the equilibrium of the wrenches $w_i$ exerted by fingers, that is:

$$\lambda_1 w_1 + \lambda_2 w_2 + \lambda_3 w_3 = 0,$$

with $\lambda_i > 0$

Besides their magnitude, the wrenches depend on geometry of the contact, therefore it is possible to find if the previous equation may admit a solution just considering the shape of the object. Moreover, in this phase also the specific geometry of the gripper has been taken into account: in fact in order to reduce the number of possible solutions, configurations too far from the ideal case (contact forces oriented as the action line of the fingers and focus of the forces coincident with the center of the gripper) are discarded.

**Step 3: Immobility**
It is well-known that, in general, it is possible to achieve frictionless force-closure of almost all 2D objects by means of 4 contact points. However the effects of the curvature may allow to immobilize an object with less than 4 fingers. In order to find a grasp, that could guarantee the immobilization of the object, the so called 2nd order mobility index $m_{q_0}^2$ [14, 15] is computed, for each possible (i.e. after Step 2) configuration. This index considers the admissible motions of the object (constrained by the fingers) in its configuration space taking into account the relative curvature between object and fingers. It has a simple interpretation: if $m_{q_0}^2 > 0$ there exist accelerations such that the object can break away from the 3 fingers.

**Step 4: Optimal grasp**
Among the configurations with the lower 2nd order mobility index (possibly 0, that is the object is immobilized), a further optimization process is performed in order to choose the “best” grasp. This last step considers the reaction forces (exerted by fingers) to an angular displacement $\alpha$ imposed around the focus of the contact normals, and tries to maximize these quantities.

Also in this choice the curvatures of the object and the fingers play a central role. In fact the momentum of the finger reaction force is $m_i = \frac{1}{2} k_i^2 \alpha^3$ where $k_i = \frac{(\rho_i - r_{C_i}) (\rho_i + r_{C_i})}{r_{F_i} + r_{C_i}}$ and $\rho_i$, $r_{C_i}$ and $r_{F_i}$ are respectively the distance of the contact point from the rotational axis, the radii of curvature of the object and of the finger in the considered point. The purpose of this procedure is therefore to obtain the maximum value of $\sum_{i=1}^3 k_i^2$.

Finally, the criteria used to find a suitable grasp configuration lead to the intuitive results, shown in Fig. 7 where a circle, a triangle and an irregular object are considered.

**5 Experimental activity**
In order to test the effectiveness of the robot arm/gripper system together with the control strategies and the grasp planner introduced in the previous Sections, a completely autonomous procedure has been developed. The desired task is to grasp an unknown object placed within the manipulator workspace and selected by the
The procedure is composed by 6 main steps:

1. The user moves the robot end-effector by means of the keyboard, the mouse or a joystick until the vision system points to the object to be grasped. Because we are currently using a single camera and considering a two dimensional model of the object, with this operation the user implicitly chooses the approach direction to the target.

2. At this step the vision system moves the robot arm in order to align the center of the camera with the object. The vision algorithm can also deal with moving objects.

3. Since the current vision system is not stereo, the distance from the target can not be estimated from a single image. Therefore the robot is moving along the camera-object direction in order to take two picture of the object and then compute the distance by means of simple geometric considerations.

4. Using previous estimation, the robot is moved in order to reach a given distance from the object.

5. The grasp planner selects the contact points on the object according to the criteria mentioned in Section 4 and computes the proper position trajectory for the end-effector in order to reach this configuration.

6. Finally, the robot is moved according the planned trajectory and the grasp performed by the gripper, as shown in Section 3.
6 Conclusions

In the present work, we have described an integrated robotic system composed by a 3-dof gripper, an anthropomorphic arm and a vision system. The end-effector, purposely designed for space applications, has a simple kinematics structure (3 parallel fingers disposed radially) and an high-level sensory equipment that make it particularly suitable for autonomous operations. In fact, the simplicity of the mechanical configuration allows to adopt simple but very reliable control strategies (by means of position, proximity and force sensors). In particular, it may be easily implemented an on-line planner to automatically choose the grasp points according to given criteria: we have successfully implemented a method based on the concept of \textit{grasp stability} rather than on more classical optimization of the external forces that can be resisted. This algorithm takes into account the mechanical structure of the gripper and the relative curvature of the object and the fingers in the contact points. Using the proposed planner, an automatic grasp procedure, able to take an unknown object selected by the user, has been implemented.

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References


