A DEXTEROUS GRIPPER FOR SPACE ROBOTICS

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ABSTRACT

The paper summarises the work done so far by four University groups involved in a joint project for the development of a medium-complexity robotic gripper, respectively developing the mechanical design (DIEM-Bologna), the sensory and control system (DEIS-Bologna), the dynamic simulation (DEI-Milano) and the sensor fusion (DII-Parma). The gripper has been designed in order to perform low- and medium-complexity space-lab manipulation tasks, aiming to achieve a trade-off between simple twin-jawed grippers and highly sophisticated multi-degree-of-freedom hands. It presents a three-finger, three-degree-of-freedom architecture and is capable of synchronous application of the grasping contacts, so that force-closure grasps can be achieved on irregularly shaped objects even floating in micro-gravity conditions. Proximity sensors and intrinsic contact force sensors installed on each finger can allow object shape recognition together with control of approaching and grasping procedures. The capability of being tele-operated is addressed as well as the possibility of accomplishing elementary tasks in autonomous way.

1. INTRODUCTION

The convenience to accomplish simple and routine space-lab activities by artificial facilities and not by astronauts is being currently acknowledged for many reasons, not least the cost of astronauts' labour. Robotic arms equipped with suitable end-effectors could substitute human intervention in many activities, operating autonomously or being tele-operated from less expensive earth-based staff.
Purposely designed facilities, e.g. pay-load tutors [1], should provide for a structured environment where the robotic accomplishment of experiments would result greatly helped.
Due to the fact that the experiments could involve the manipulation of objects of quite different nature, (not only "technical" objects but also biological or natural items) the determination of a suitable gripper architecture must be inspired to very particular issues, including the capability of shape adaptation with fine control of grasping forces (soft grasping).
To this purpose, dextrous articulated hands can be considered a suitable solution for future space application and great effort is still given to their development [2,3]. As a matter of fact, anthropomorphic hands seem to be highly performing solutions for generalised skilled tasks, both for their intrinsic versatility and for being the easiest man–interfaceable end-effectors for tele-operation.
However, in a wide class of space manipulation tasks, a high kinematic complexity of the gripper could not be necessary or, when available, be very partially exploited.
A family of intermediate configuration grippers, not so elementary as twin jaw grippers but not so complex as multi-fingered articulated hands, could therefore represent a valid trade-off between the achievable functional capability and the overall complexity, bulk and cost. Efforts in this direction have been proposed even in recent years (see for example [4-6]).
The activity reported in this paper, jointly performed by four University research groups with financial contribution by A.S.I. (Italian Space Agency), was specifically addressed to define a medium-complexity gripper and to test its actual manipulation capability in the perspective of use in intra-vehicular experiments in micro-gravity conditions, with levels of autonomous operation as well as remote operation capability.

2. THE GRIPPER ARCHITECTURE

The choice of the kinematic architecture of the gripper has been conditioned by the assumption that three-point adaptable grasps should be the main design goal and that no more than three actuators should be used. Another mandatory goal was to get the possibility of simultaneous

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application of the contacts on the object to be grasped: as widely demonstrated by simulation, a synchronous application of the constraints can help reducing uncontrolled movements of objects freely floating in micro-gravity space during the approach phase.

The mechanical design has been developed, so far, assuming size and weight compatibility with the ASI Spider Arm [7].

A detailed discussion about the choice of the kinematic configuration has been reported in [8-10]. We present here the final features that are being implemented in the gripper prototype, that has been designed for laboratory evaluation and does not cope yet with space application specifications as to materials, sub-components and processes.

The general architecture of the gripper is shown in Fig.1.

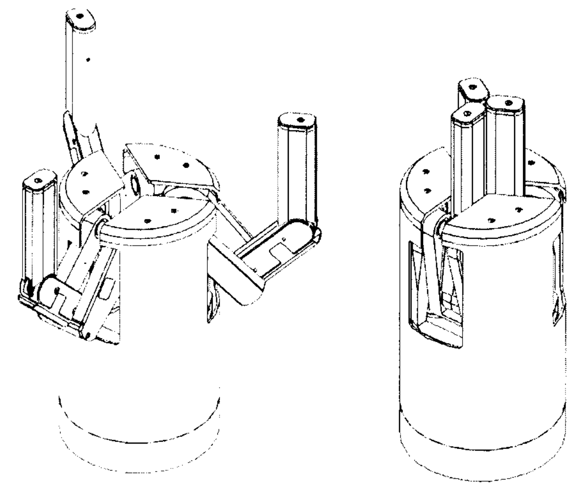

Fig. 1 A general view of the gripper

Three articulated fingers are equally spaced and contacts can occur along three intersecting coplanar lines. Each articulated finger has a distal phalanx that gets in touch with the object and two intermediate phalanxes, coupled by means of cable transmissions, that allow translation of the distal link.

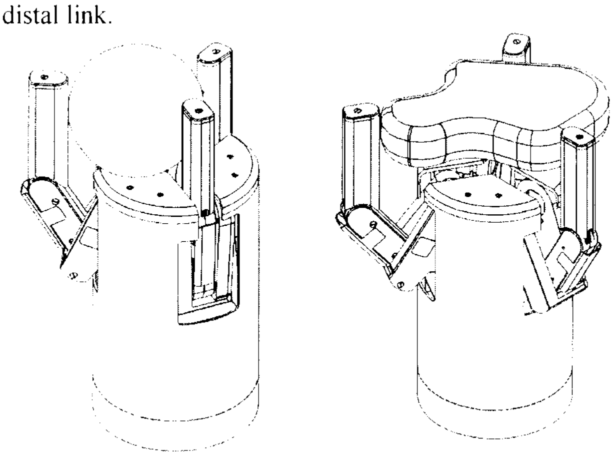

Fig. 2 Two examples of possible grasp configurations

In addition to the advantage of using only revolute pairs, this kind of kinematic structure presents a high ratio between maximum and minimum extension, obtaining a very large workspace with respect to the size of the gripper body.

Because the three fingers can move independently, the grasping configuration may be any triangle having vertices on the approach trajectory segments. Two examples of possible grasp configurations are shown in Fig. 2. The gripper adopts a modular architecture. A view of each finger module is shown in Fig. 3, together with a scheme of the internal cable transmission. The actuation of fingers is provided by three linear actuators manufactured by Wittenstein Gmbh according to the model of the artificial muscle developed at DLR [2]. A purposely designed sensor based on a Hall effect transducer is connected to the rod for position measurement. Further details about the mechanical transmission can be found in [8-10].

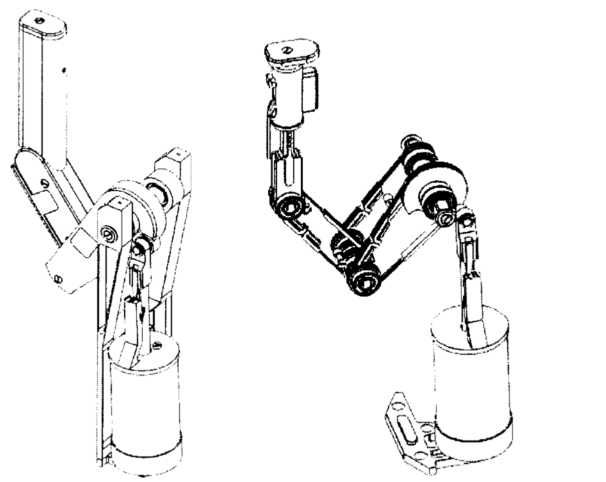

Fig. 3 The single finger module and its internal cable transmission

The sensory equipment installed in each finger is visible in Fig. 4, and consists of an optical proximity sensor and a miniaturised intrinsic tactile sensor (based on a multi-component force/torque sensor) [11]. This basic equipment allows the control of approach movements of each finger, with simultaneous reach of contact, and the control of grasping forces once the contacts have been applied.

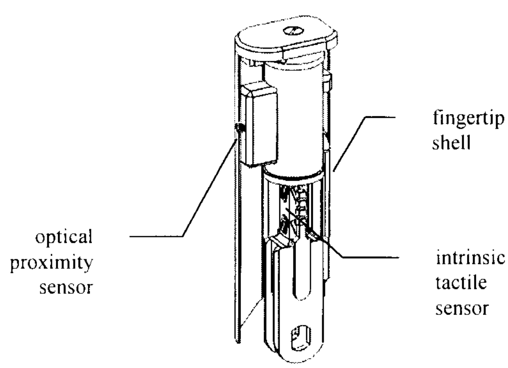

Fig. 4 The sensory equipment placed on each fingertip

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 sensors allow for efficient recognition and control of contact conditions, included incipient sliding. This basic arrangement does not exclude the possibility of further integration with additional sensory equipment, like distributed tactile sensors, stereo vision or more sophisticated scanning devices.

3. COMMENTS ON THE MECHANICAL DESIGN

A potential drawback of the adopted kinematic configuration is that the achievable three-point force-closure (precision grasp), even if adaptable and synchronous, may be not sufficient to satisfy the demand of grasp robustness in space manipulation. This could be better guaranteed by form-closure configurations (encompassing grasps). Without back-drawing from the initial choice of using the few available degrees of freedom in order to get, first, synchronous precision grasp (useful in micro-gravity operations), some solutions are under evaluation in order to add some level of form-closure capability. A simple solution might consist in purposely shaping one fingertip in order to allow multiple contacts along the same finger.

Other solutions, requiring at least an additional degree of freedom, could be obtained by changing the reference angle of the internal fixed pulleys that determine the posture of the distal phalanx or the direction of its approach linear trajectory. In both cases the front surface of the gripper body should act as a palm surface (Fig.5).

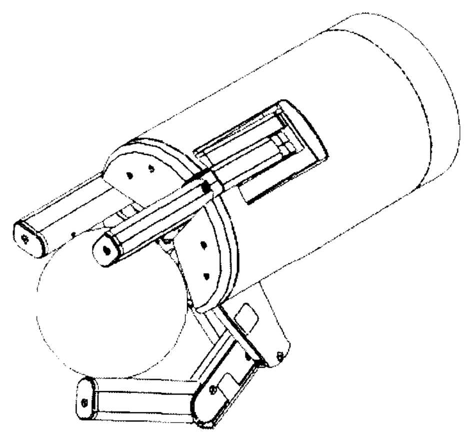

Fig. 5 Form closure by changing the approach trajectory of one finger

As to the prototype design, it can be observed that its final size has been conditioned by the use of off-the-shelf actuators that were oversized with respect to the actual need of thrust and stroke. A purposely design of the actuators could further reduce the size and the bulk of the gripper body, particularly its length.

In conclusion, the proposed robotic gripper exhibits some interesting features that can make it suitable for application whenever the operating capability of a parallel jaw gripper is not adequate and, at the same time, the complexity of a multi-fingered articulated hand is not acceptable. The main advantages of such a device are:

- it is not very complicated as to kinematics, actuation and control, using only three actuators and three degrees of freedom;
- it can provide adaptable and synchronous application of contacts to objects of any shape, thus allowing to grasp objects not centred with respect to the gripper axis of symmetry, without disturbing their initial posture;
- it presents a very large workspace with respect to its body size, and is capable of operation both on small and on large objects;
- force-closure grasps can be integrated by some capability of form-closure grasp;
- it adopts a sensory equipment suitable for allowing both autonomous and tele-operated procedures by means of a three-finger interface.

4. OPERATION AND CONTROL

The gripper will be tested both in autonomous operation and as tele-operated system. For the former goal, several strategies are under evaluation and will exploit the available sensory capability and the possibility of independent controlled motion for each finger.

A typical autonomous task could be articulated in the following phases:

- approach motion in fully open configuration to the space region where the object is expected to be;
- object surface scanning by means of the proximity sensors mounted on the fingers: this operation should be aided by combined movements of the fingers along their approach direction and of the robotic arm and wrist; the object should not be touched in this phase;
- choice of the optimal grasp configuration, to be computed by means of proper algorithms for the optimisation of the three-point grasp;
- synchronous application of contacts and control of the grasping forces during the manipulation of the object.

Concerning tele-operation tasks, the definition of a suitable interface with the operator is a major issue. A solution currently under evaluation consists in a set of three wire-driven fingertip interfaces [12]. Haptic sensations connected to the three contact grasp on a virtual object can be reproduced by proper control of wire tension and elongation. Due to the different kinematics of the gripper and of the human fingertips, the virtual object should be properly scaled and modified with respect to the real object. Work in this direction is at a very early stage.

As to the set-up of the gripper prototype, in this initial phase of activity it has been decided to use, as long as possible, standard hardware/software components for controlling the gripper and evaluating its capabilities. The adopted architecture consists in a PC equipped with a DSP (TMS320C32) board and connected with the motor drives and to an input board for the sensors. This board has been purposely designed because of the relatively high number of signals (30) to be acquired in real-time. From the software point of view, besides a real-time kernel on the DSP board, an interface between the DSP and the PC has been developed, allowing to use in an integrated fashion both real-time software and high-level environments for user interface.

5. DYNAMIC MODELLING, AND SIMULATION

Dynamic simulation is based on MOSES, a Modular Object-oriented Software Environment for Simulation developed at DEI. In MOSES, dynamic models of multi-body systems are built by assembling basic models (modules) and their aggregates through a graphic interface. Modules are defined through a Model Definition Language (MDL), which is "natural" for the analyst and fully "declarative". This is opposed to a "procedural" form, where a relation of causality between inputs and outputs is made explicit. Furthermore, standard module interfaces are defined to avoid the replication of models of the same physical component in case of different boundary conditions or different sets of exported variables. The complexity and variety of the data defining a complex technological are managed in MOSES by structuring modelling data in an Object-Oriented database.

Since for complex systems the raw assembly of declarative equations results in a largely redundant DAE system, a symbolic manipulation software has been developed in order to gain computational efficiency [13], [14]. The symbolic manipulation essentially aims at splitting the global DAE system into almost independent subsystems and at minimising the order of the implicit system to be solved.

On the other hand, when the modelling of mechanical systems is of concern, tools for 3D solid modelling turn out to be essential for both model building and 3D rendering of motion. To this aim, a 3D solid modelling interface, ROSE (RObot Solid modelling Environment) has been developed. It allows the geometric and kinematic modelling of a robotic system and generates the topological data for the automatic generation of the MOSES dynamic model. ROSE was designed to strictly match the modular approach of MOSES, in terms of a one-to-one correspondence of the graphical entities with their MOSES dynamic modules (or sub-models) counterparts and in terms of a correspondence between the data structures of both environments.

The dynamic model of the mechanical structure (plant) is then automatically generated in the MOSES environment, where a control system can be also attached to the plant. The ultimate output of the simulation environment is the 3D rendering of motion, implemented in VRML (Virtual Reality Modelling Language). This has been made possible by the adoption of a solid modelling library based on a boundary representation of solids which matches the VRML format.

The Gripper Model and the simulation of grasp

Each finger of the 3 dof gripper is a serial chain of three links connected by rotary joints and additionally constrained by the tendons, which maintain the last phalanx parallel to the wrist (approach) axis while moving. Actually, the tendons have been modelled as extensible, taking into account their elastic stress/elongation characteristics.

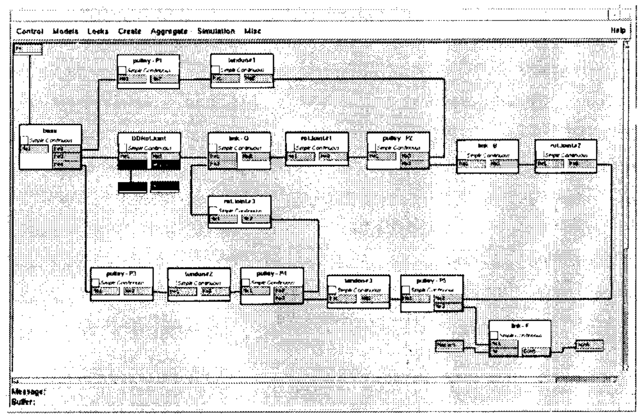

Fig. 6. The block scheme of the finger model

The chain structure is reflected in Fig. 6, where the MOSES block scheme of the model finger is shown. Each module in Fig. 6 defines a simple model and represents a well identified part: rigid body (links and pulleys), rotational joints, tendons. Aggregation is performed by establishing a one-to-one connection between two identical ports: the mechanical terminals.

Note that three mechanical terminals are not connected to any other terminal and can be reported at the upper level. These free terminals of the finger aggregate model are available for connecting the finger to the wrist sub-model and for representing the interaction of the finger with the grasped object sub-model, respectively.

As an example of achievable simulation results, let us consider the grasp of a cylinder in the absence of gravity, shown in Fig. 7. As it is clear from the Figure, which shows the co-ordinate of the centre of mass of the cylinder along the axis, immediately before t=5 s fingers 2 and 3 hit the cylinder, which starts moving towards finger 1. Then, after some bounces, all the fingers come in contact and the cylinder stops.

6. SENSOR FUSION TECHNIQUES

The control and tele-programming architecture of the gripper incorporates a technique for fusing information provided by tactile and IR proximity sensors. The technique is based on the construction of volumetric approximations of the explored object and enables approximate shape reconstruction, recognition of convex subparts, and generation of efficient exploration strategies [15], [16]. Multiple polyhedral representations of the object are exploited to deal with different types of sensory information.

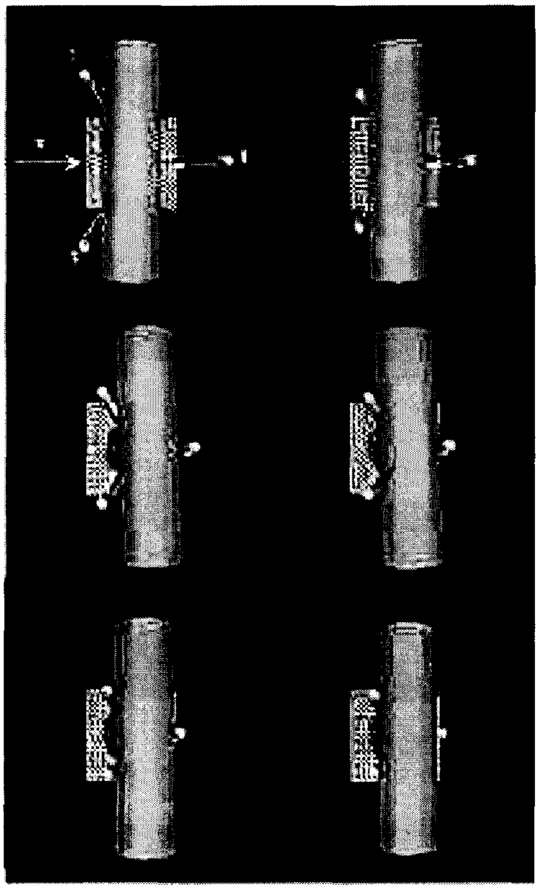

Fig.7 Animation of a grasp simulation in absence of gravity

The sensor fusion technique can cope with arbitrary shape classes, but may require prior volumetric segmentation to enable direct shape reconstruction and recognition of convex subparts. The *Enveloping Polyhedral Model* (EPM) is an upper approximation of the object exploiting perceived contact locations and normal directions at the contact points provided by IT sensors. At the beginning of the exploration an EPM equals the whole workspace. As contact points are accumulated, the EPM volume decreases, because of the ``slicing" effect of contact planes on the workspace. The shape approximation returned by the EPM can be further refined by taking into account the partial containment of the object inside the volume spanned by the gripper's palm and fingers. The *Inscribed Polyhedral Model* (IPM) is built from proximity information provided by IR sensors and contact locations returned by IT sensors, but does not require contact normals (which could be noisy or unavailable). Under the hypothesis of part convexity, this representation is computed as the convex hull of the available data points. Since an IPM is always contained in the corresponding EPM, their joint availability enables efficient recognition and exploration strategies [16]. Figure 8 shows the concurrent refinement of EPM and IPM on increasingly larger data sets.

7. TELE-PROGRAMMING ARCHITECTURE

The reference architecture for tele-programming and monitoring of the gripper consists of a *client-server architecture* where the server and one or more remote client systems are interconnected using TCP/IP. Use of a standard IP-based protocol enables direct exploitation of any enhancement in quality of service brought by Internet-related technologies. Recently, a number of tele-robotics projects have been based upon Internet infrastructures, including projects aiming at monitoring of space-robot operations, e.g. [17].

The *server* system application can operate directly on the same PC hosting the DSP for gripper control, or on a separate, locally-connected workstation providing a single access point to both the gripper and the carrying arm. The server has been implemented as a multithreaded C++ application based on the OmniORB2 multi-platform library and is fully portable across most standard operating systems. The server supports activation of gripper motion tasks with local control or under tele-operation, remote system supervision during task execution, and visualisation of the current operating environment, i.e., live feed of raw or processed sensory data. The server architecture comprises a number of concurrent threads providing system supervision, network interfacing, authentication and synchronisation of incoming client requests, and interaction with the local control system of the robotic device, while actively managing Quality of Service [18].

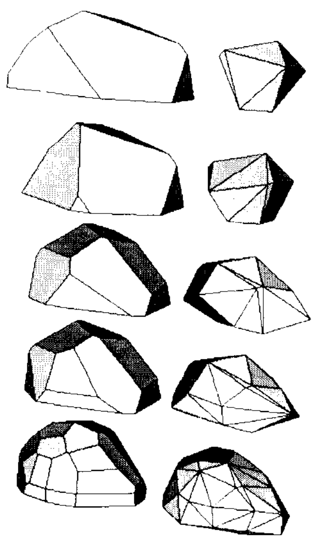

Fig.8 Refinement of EPM and IPM

A Java-based *client* is under development to assist users in their remote interaction with the gripper by means of the server system application. The client program offers a main set of functional modules including parameterisation and execution of dynamic simulations, task programming, monitoring of task progress, and 3D visualisation of sensor fusion. Task programming is currently supported only in terms of specification of elementary finger and gripper motions, possibly terminated by a sensory condition. Task progress is shown by providing the user with a VRML animation of the scene fed with the current pose of the gripper as obtained from the server. Raw and filtered sensory data from the robotic system are also available and can be parametrised by the user, including an optional live feed from a video camera. As an additional feature, the haptic perception of the gripper can be shown in terms of the current EPM and IPM built from the fused sensory information in the same VRML scene including the gripper. The adopted client implementation technologies, namely Java and VRML 2.0, are *de facto* standards oriented to mobility and interoperability.

7. CONCLUSIONS

The current development stage of a project for the design and implementation of a dextrous gripper oriented to space applications has been described. The gripper presents some interesting features that can make it suitable for precision grasp on known-geometry objects as well as for adaptable synchronous grasp on irregularly shaped objects. Together with the development of a prototype, tools for dynamic simulation, sensor fusion and tele-programming have been defined.

The results obtained so far encourage the prosecution of the programme.

After the completion of the prototype, expected at the end of June 99, activity will mainly be devoted to laboratory experiments in autonomous grasping operations, with the gripper mounted on a Comau SMART 3S arm.

In parallel, a three-fingered wire-driven interface will be developed in order to perform tele-operation experiments.

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