TAR: A Twin Arm Robot for Dexterous Assembly and Maintenance Tasks on ISS

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Abstract

By mid 2002 crew time will become a precious resource on ISS. Especially EVA activities will be under pressure, requiring special training, preparation and post-sortie recovery. The key issue is a collection of human scale dexterous manipulation tasks, like handling MLI and connectors. A significant portion of these tasks is well-predictable and can be considered routine operations. But they are beyond the capabilities of the current ISS robots. This paper describes a concept for a small, dexterous and relatively autonomous two armed robot TAR, that can support the crew in routine assembly and maintenance tasks. Early prototyping activities are showing that there are no major technical obstacles. The main challenges are to come up with an affordable flight development schedule and to obtain political and financial commitments.

Introduction

With the arrival of the Service Module (Zvezda) last summer, the International Space Station has obtained a capability to support a three person permanent crew. Today, the crew is on board. Although there will be some time to start with early experiments, the main focus of this crew will be the expansion of the station itself. In a rapid succession, modules follow, until the assembly sequence is formally completed in 2006.

The larger modules are typically brought to the station in the Space Shuttle. The shuttle visits are interspersed by regular visits of Progress cargo vehicles, the European cargo ATV and the Japanese HTV, adding up to an average of one visiting vehicle every 6 to 8 weeks. While the Station is expanding, more and more experiments come available, increasing the pressure on the crew to spend time on experiment tending. At the same time, the growing number of modules being continuously exposed to the harsh LEO environment will require more and more maintenance.

The nature and the amount of maintenance tasks to be expected can be derived from the MIR history [1]. The need for robot support on ISS can be derived by extrapolating the 3 person MIR crew to the 6 person crew on the 5 times larger ISS. Also a closer look at the early ISS history is quite illustrative. On each manned flight to the early ISS, maintenance tasks were performed. On flight 2A, the Zarya battery charger was replaced and jammed antennae were freed. On flight 2A.1, some S-band boxes were replaced, battery regulators were exchanged and sound mufflers installed. On flight 2A.2, the S-band omni antenna was replaced, another S-band box was replaced and 6 Zarya battery boxes were exchanged.

By mid 2002 crew time will become a precious resource. Especially EVA activities will be under pressure, requiring special training, preparation and post-sortie recovery. The key issue is a collection of human scale dexterous manipulation tasks, like handling MLI and connectors. A significant portion of these tasks is well-predictable and can be considered routine operations. But they are beyond the capabilities of the current ISS robots.

This paper further describes a concept for a small, dexterous and relatively autonomous two armed robot TAR, that can support the crew in routine assembly and maintenance tasks. After briefly describing typical tasks for a dextrous robot, we present technologies, components, and prototypes that were realised to date at Fokker Space.

System Concept

A key design feature of the TAR system is *compatibility with the dexterity of a human* astronaut performing EVA. Because of this compatibility, TAR can use existing ISS and EVA infrastructure, like handrails and connectors. Therefore the use of TAR does not require any costly adaptations to the ISS infrastructure.

Compared to the large robot arms on ISS like SSRMS, SPDM and ERA, TAR will have a *high degree of autonomy*. It will be able to work for several hours on battery power, needing no physical connection to ISS other than a foothold or handrails to offset reaction forces. When working for longer periods outside, TAR will plug itself in to an existing EVA power connector.

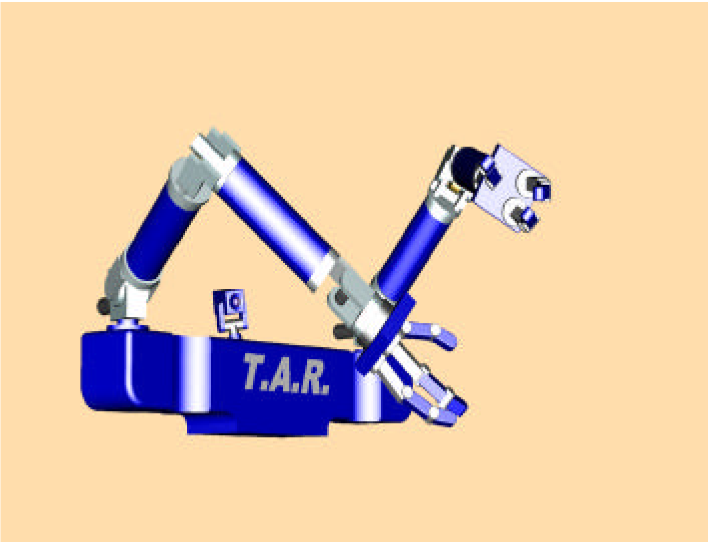

Fig. 1 TAR: Concept for a Two Armed Robot for routine assembly and maintenance tasks on the International Space Station

TAR is designed to operate in various modes, depending on the tasks. Using its two arms and dexterous grippers, TAR is able to relocate itself *using the EVA infrastructure*, but can also operate from the tip of ERA. TAR's dexterous hands can handle human compatible EVA tools. Alternatively, each dexterous hand can be exchanged and replaced by a tool for a specific task, such as welding.

A new generation of on-board space compatible micro-processors in TAR will increase its *autonomous decision making* and sensor control capabilities, but they will still be no match to human reasoning. Focusing on routine maintenance, the baseline mode of operations is pre-programmed, *supervised from the ground*, communicating via a radio link. TAR is small enough to fit in an airlock for maintenance inside ISS.

Tasks

In the spectrum between the well-structured environment of an automobile assembly line, a major domain for industrial robots, and the unpredictable terrain conditions encountered by the modern day exploratory robot rover, the operational environment of TAR, the outside of the International Space Station is relatively well structured.

The tasks to be performed are quite predictable, although not necessarily planned a long time ahead. The tasks typically include the exchange of equipment boxes and experiments, in a very wide range of shapes and interfaces and fixation mechanisms [2,3]. There are many interfaces between units not intended for (scheduled) maintenance on orbit, but that still offer EVA compatible design, down to simple details like the use of captive bolts and standard nut sizes.

After many task discussions with robotic experts, payload specialists, station designers and astronauts and cosmonauts with SRMS, MIR cargo boom, EVA and MIR experience, the following design challenges stand out:

1. The need for two co-operating operational arms (hold and fix)
2. The need for dexterous end effectors (generic grapple tool with limited fine manipulation capabilities)
3. The central role of contact motion (and the problem of easy but clearly specifying contact motion to a robot)

Specifications

The main requirements for TAR stem from the chosen compatibility with humans, the typical maintenance tasks, and from the fact that TAR will have to operate in a quite harsh environment.

- TAR will be able to grasp and manipulate objects from paper thin to 200 mm cube
- The two arms of TAR have a shared (2-arm) working range of a 700 mm cube
- TAR will be able to work 8 hours on batteries
- The TAR mass target is 50 kg
- The stowed volume target is a 50 cm cube
- The power consumption is 100 W nominal and 500 W peak

Light weight dexterous arm

At the core of the TAR system are two, lightweight dexterous robot arms. The combination of required dexterity, size and motion range has led to the selection of a 7 DOF (Degrees Of Freedom) configuration, with human like limb lengths.

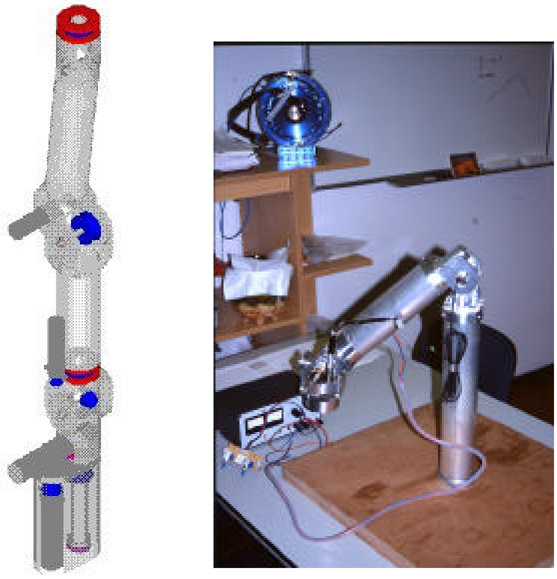

Fig 2. Light weight dexterous arm. Left: concept, right: electromechanical prototype

Each arm has a shoulder, an upper arm, an elbow, a lower arm and a wrist. The shoulder has a radial, hinge and radial joint configuration, the elbow has a hinge joint and the wrist has a universal and a radial joint totalling 7 joints. The arms are about 700 mm apart, both the upper and lower arm have a length of about 425 mm. The gripper subsystem adds some length between wrist and tool centre point. The whole configuration is very similar to a human torso.

A major design decision was to make the arms relatively strong, compatible with operation under 1G conditions (although allowing reduced performance). Working with relatively small, high performance DC motors to keep within the tight mass budget, this leads to high gear transmission ratios and on intrinsically not backdriveable drive train. The initial transmission stages are based on planetary gears, while the final transmission stage is implemented by worm gears. To maintain possibilities for simple and robust programming as explained later, joint level torque measurement was introduced.

The mechanical structure consists of milled aluminium parts and tubing. The motor control boards are a further development of the ones we have used in the Very Large Telescope Delay Lines project [6]. The arm level controller is based on a novel implementation of impedance control and runs on an embedded industrial PC. We currently work on a first electromechanical prototype, expected to be completed January 2001 (fig. 2).

Compact Dexterous Gripper

The TAR concept is based on the use of generic dexterous end effectors. We developed a multi-fingered dexterous hand, with motor level torque control and finger tip level impedance control for a smooth control of the grasping force over a human like range of grasps.

Fig. 3 Prototype compact dexterous gripper with 12 active joints

The gripper was designed to provide a high grasp force, various wrap grips, but also two and -three fingered precision grips with fine motion capabilities with grasped objects.

A first prototype was built and tested (fig. 3). This prototype had 3 fingers with 4 joints each, 12 controlled joints in total. An important design goal was to use off-the-shelf technology where possible. The prototype turned out to be relatively heavy and bulky, but was able demonstrate major design characteristics. Grip range and motion range exceeded the specification. The motor and snare drive concept could in principle handle the specified load (50 N at the finger tip), but the final stage of the planetary transmission proved to be a weak point. Co-ordinated motion was successfully implemented on a single finger (4 joints). Duration tests ruthlessly exposed a critical dependence of the mechanical design on pretension in the snares.

A new drive train was designed to reduce the volume and definitely prove the motion capabilities. However this design was abandoned when it became apparent that it would still suffer from some of the same drawbacks as the first prototype.

In the mean time we have started to design a third generation dexterous gripper prototype. For a first impression see fig. 1.

Effectively controlling contact motion

A third technology focus in the TAR project is to achieve easy programming for contact motion and dexterous gripping.

A Task primitive library was constructed with the following objectives:

- Shield the user from low-level control-parameters.
- Create an easy-to-use task-programming language.
- Make a controller easily adaptable to new hardware.
- Let controller work with limited computing-power.

Library construction started from a selection of all English verbs based on contact motion semantics, initially giving a list of 712 verbs. The list was reduced to 62 verbs by eliminating verbs with multiple meaning (e.g. *put*), verbs non-single word form (e.g. *pick up*), and complex action verbs (e.g. *install*). Verbs indicating the use of specific tools (e.g. *waxing*) were removed, but can be used in additional libraries. The final selection of the verbs was done by, as closely as possible, matching the primitives with the primitives already used in ESA robot projects like SPARCO and ERA.The task-primitives have been ordered according to the tool-tip transition and the resulting library is given in Table I.

TABLE I
TASK PRIMITIVES FOR CONTACT TRANSITIONS

Transition	Primitive
No contact: translation	**move**
No contact: rotation	**turn**
From no contact To contact	**touch**
From contact To no contact	**extract**
Contact: Forces	**press / pull**
Contact: Moments	**torque**
Contact: position	**rub**
Contact: rotation	**screw**
Contact: special	**insert**
Reduction of interaction	**relax**

A subset of these task primitives was implemented in a test set-up with an industrial COMAU robot using the Open Controller and a proprietary impedance controller on top in our laboratory. Adjectives like “fast” and “careful” were introduced to shield the users from details like spring constants and damper settings. Experiments with novice robot programmers showed that the use of motion primitives was both intuitive and efficient. The programming time for a reference mission was significantly reduced.

Impedance control

Commercial robot controllers explicitly control position or force and need precise information about the environment. TAR has to interact with an environment in which this information is not available or not precise enough.

In TAR we use a novel implementation of impedance control [4,5]. The controller is intuitive, intrinsically passive and stable in all situations including free motion, contact motion and also the transition between both.

The controller is intuitive because it has a simple physical interpretation: it can be described in terms of simple physical components like springs, dampers and masses. Take for example the following controller (fig. 4):

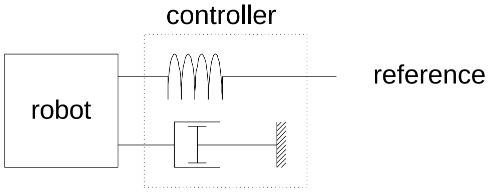

Fig. 4: Simplified impedance controller

The robot system to be controlled is represented by a single mass. The spring and damper are virtual elements and simulated inside the controller. A motion task is represented as moving the reference point. Instead of transmitting the movement of the reference point directly into the robot, the reference motion stretches the virtual spring in the controller to exert a virtual force on the robot. This force is translated into setpoints to the real robot.

If the real world robot is constrained by its environment and cannot follow, the virtual spring makes the robot exert a force on the environment. The virtual damper is added to ensure proper transient behaviour and asymptotic stability. In practice implementing a virtual damper is difficult because the actual velocity of the robot is needed which is often not available. The solution is called damping injection (fig. 5)

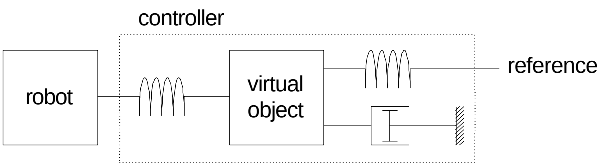

Figure 5: Simplified impedance controller with damping injection

The controller is expanded with a virtual object and a second spring. Now implementing the virtual damper is easy because only the velocity of the virtual object is needed and that is known because it is simulated inside the controller. If the virtual spring between the robot and the object is chosen to be relatively stiff the robot and the virtual object are well coupled so the velocities of the robot and the virtual mass are approximately the same. Kinetic energy from the robot is transferred to the virtual object and dissipated in the damper. Damping is injected into the robot.

As the controller can be described in terms of passive physical components like springs, dampers and masses, it is intrinsically passive. For a constant reference the system is always asymptotically stable. This is because the system contains damping so energy in the system always decreases. For a non-constant reference the amount of energy supplied to the system can be controlled.

The TAR control system is based on a hierarchy of such impedance controllers: finger, hand, arm and arm co-ordination, all controllers work according to the same principle.

Co-ordinating multiple controllers

By sharing one virtual object between multiple controllers, co-ordinated motion is achieved in a straightforward manner. The advantage becomes clear if we consider multiple fingers in a hand (fig 6). Each finger is connected to the same virtual object with its own finger-object spring. The virtual object is connected with a spring to the reference and with a damper to the world.

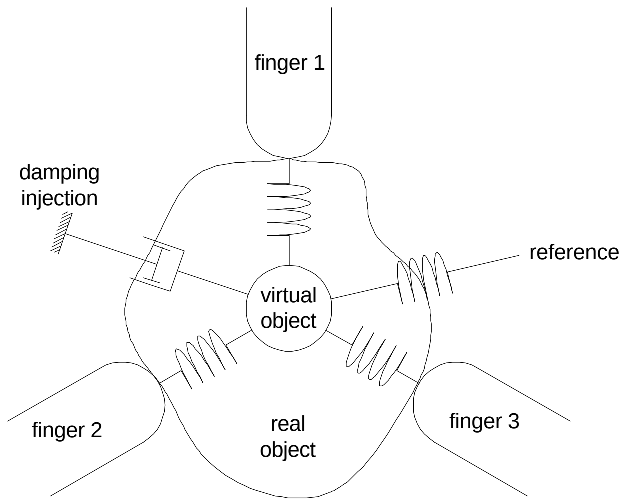

Fig. 6: Co-ordinated impedance controller for a 3 fingered robotic hand

First we give the virtual object a certain size, larger than the real object. Now we can put a real object between the fingers, more or less in the same place as the virtual object. Decreasing the rest length of the virtual object springs (shrinking the virtual object) makes the fingers move in, exert a force on the real object and grasp it. Decreasing the rest length (shrinking the virtual object) even further tightens the grasp.

By moving the reference the object can be manipulated. If the reference is moved the reference-object spring makes the virtual object follow. Some of the virtual finger-object springs are stretched while others are pressed and exert a force on the fingers. The fingers exert a net force on the real object and the real object follows.

Advance knowledge about the material of the real object can be used to match the stiffness of the virtual finger-object springs to the stiffness of the real finger to real object contact, e.g. using relatively soft springs to grasp an egg and stiff springs to grasp a screwdriver. Conversely, by analysing the compression of the virtual finger-object springs during grasping, we can extract valuable information on size and surface stiffness of an unknown object. Advance knowledge about the rough shape of the real object (e.g. from a vision system) can be used to pre-shape the grasp

Implementation

The implementation of the control algorithm is relatively simple. It only needs a simple model of the robot with the forward kinematics and the Jacobian and a few sensors. No backward kinematics that can have multiple or no solutions, no inverse Jacobian that can be singular, and no dynamic model that is often inaccurate are needed.

We do need joint level position sensors, but not extremely accurate ones. No velocity measurements are necessary, in real systems often not available anyway. However, if the robot is not backdriveable, force sensors are needed..

The main computations consist of the simple kinematic model and the simulation of the dynamics of the virtual mass, springs and damper. The computational load is relatively low.

Conclusion

This paper describes a concept for a small, dexterous and relatively autonomous two armed robot TAR, that can support the crew in routine assembly and maintenance tasks. Key components are a dexterous gripper, a light weight arm, and a command and control environment that allows for simple and robust commanding of motion primitives, especially in controlling the forces in contact with the environment.

The need for TAR-like systems on ISS is obvious, there will simply be not enough man power available. The prototyping activities are showing that there are no major technical obstacles. The technology is maturing and can be implemented with conventional and state-of-the-art hardware. A relatively short development schedule for the development of a flight version of TAR appears feasible. The main challenges are to put the right experience together, come up with an affordable flight development schedule and to obtain political and financial commitments.

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