Design and performance simulation of TORVEastro three-link astronaut robot

F Samani and M Ceccarelli

1LARM2: Laboratory of Robot Mechatronics, University of Rome Tor Vergata, Rome, Italy

Email: francescosamani83@gmail.com

Abstract. In this article TORVEastro, a three-link astronaut robot, is presented with a conceptual design that is used also for a CAD design in performance simulations. This TORVEastro robot is designed for service applications in space stations. Requirements and characteristics are discussed with the aim to identify design problems and operation features. A study of feasibility is discussed through performance evaluation by using kinematics and dynamics simulations whose results show the feasibility of TORVEastro robot operation and its peculiarities.

1. Introduction

With the development of space technology, more complex space tasks will be carried out in the future. Compared with astronauts, it is advantageous to use space robots instead of human beings and therefore, space robots are increasingly playing a key role in on-orbit servicing operations. Since more than ten years, great attention has been paying to service robots, for the development of new robotic systems for applications even in non-technical areas [1]. Typical robots are already developed for medical care, space exploration, demining operation, surveillance, entertainment, museum guide. In some cases, the results have already come available on the market and in considerable literature about service robot is available not only on technical problems but it is reported in no-technical paper for space [2]. Advancements in interaction between a human and a robot, derives from the need for even more efficiency, flexibility and productivity, in a space contest, as well as for reduction in the human stress, risk and workload as pointed out for example in the paper of G. Michalos and his collaborators [3].

According to the International Federation of Robotics (IFR), "a service robot is a robot, which operates semi or fully autonomously to perform services useful to the well being of human and equipment, excluding manufacturing operations" [4]. According to ISO 8373 [5] service robots require "a degree of autonomy", which is the “ability to perform intended tasks that are based on current state and sensing, without human intervention”. For service robots this ranges from partial autonomy - including human robot interaction - to full autonomy - without active human robot intervention. The International Federation of Robotics (IFR) statistics for service robots include systems based on some degree of human robot interaction or even full teleoperation as well as fully autonomous systems.

Currently an astronaut robot in-operation is Robonaut (NASA), a humanoid robot that has been developed project presented by the Robotics Laboratory at the Lyndon B. Johnson Space Center (JSC) of NASA in Houston, Texas [6]. Robonaut tasks require to work alongside the astronauts (Robonaut can use space instruments and work in similar environments suitable for astronauts). The latest version
of Robonaut, R2 is the first robot that is built in the US for the ISS (International Space Station), and it is was delivered by STS-133 in February 2011. It is a robotic torso that is designed to assist crew with EVA (Extra Vehicular Activity) and may contain tools that are used by the crew. However, Robonaut 2 does not have adequate protection to exist outside the space station and improvements and modifications would be needed to allow it to move around the station.

Another astronaut robot is Rollin' Justin from ESA, it has four-finger hands; Its mobile base allows autonomous operation over a long range [7]. This space robot consists of a system of light arm with light arm with four-fingered hands which makes it an ideal platform for operating for sensitive manipulations. The mobile base of this space robot allows autonomous operation over a long range. Motion detection sensors and cameras allow reconstructions of the robot environment. Unstructured, variable and dynamic environments require the space robot to act independently and without human support. The Justin robot is able to work safely with people. Its multiple degrees of freedom enabled Rollin' Justin to pursue multiple goals simultaneously while respecting a hierarchy of tasks. For example, the robot can serve drinks by observing the environment, moving without singularity, avoiding collisions, responding in a manner consistent without collisions with the environment.

Kirobo is Japan's first robot astronaut (JAXA) [8] that was developed by University of Tokyo and Tomotaka Takahashi in cooperation with accompany Koichi Wakata, the first Japanese commander of the International Space Station. Kirobo arrived on the ISS on August 10, 2013 on JAXA's H-II Transfer Vehicle Kounotori 4, an un-manned resupply spacecraft launched August 4, 2013 from Japan's Tanegashima Space Center. Kirobo is about 13 inches tall, 7 inches wide and about 6 inches deep. He weighs about 2 lbs. and speaks Japanese [9]. The robot's capabilities include voice and speech recognition, natural language processing, speech synthesis and tele-communications, as well as facial recognition and video recording.

The characteristics of a space environment are related to low air pressure, large thermal excursions, high radiations and microgravity. In this regard, human beings in space require a life support system that is broad, flexible and complex. Therefore, it is important the implementation of an environmental control system and a rescue system, and this requires a lot of uninterrupted material supply [10].

In this paper the problem of designing a space service robot is attached so that it can support human being in space station. The analysis of a CAD modeling and a performance evaluation are carried out for a feasibility analysis.

2. 3-link astronaut robot design

The International Space Station (ISS) is a space station, as a habitable artificial satellite, in a low Earth orbits. Its first component was launched into orbit in 1998, with the first long-term residents arriving in November 2000 [11]. The ISS serves as a microgravity and space environment research laboratory in which crew members conduct experiments in biology, physics, astronomy, meteorology, and other fields [12]. ISS is equipped with handrails that are positioned on the outside surface to help the astronauts in the movement.

It is difficult to transport large or heavy objects from the ground into a space station [13]. The design of the space robot has to respect the requirements of the operations in the space station but, at the same time, its mass and volume should be as small as possible [14]. The characteristics of the proposed TORVEastro design are (fig. 1):

- the total degrees of freedom are 9;
- an occupied volume of 25 cm x 25 cm in the closed configuration;
- a total mass of the space robot less than 25 kg;
- robot arm length of 70 cm.

The TORVEastro space robot has a cylindrical body design with three legs, each of which is made up of two links and an end-effector. The symmetrical geometry of the legs makes them interchangeable thanks to the possibility of adopting a structure with multi-functional end-effectors. The conceptual design shows how one or two legs can be used for the most varied activities. The cylindrical body of the robot consists of curved surfaces and TORVEastro offers the possibility of
facilitated movement in the outdoor space of orbital stations in order to be able to reach the localization objects. The service robot can move along, on the rods and handrails. In fig. 1 the conceptual design is shown with geometric and motion parameters.

3. Mechanical design and features
The proposed design of TORVEastro consists of a trunk and three legs. Control boards, sensors, battery and motors can be installed inside the cylindrical body (fig. 2). The moment of inertia of the robot in the center of mass of the TORVEastro is: $P_x = 0.84 \text{ kg m}^2$; $P_y = 1.1 \text{ kg m}^2$; $P_z = 1.7 \text{ kg m}^2$. Calculations of the center of mass of the space robot have been performed in different configurations and the results show a proper dynamic capacity of TORVEastro. All electronic and sensitive parts can be repaired easily since the structure is easily accessible in each of its parts. The cylindrical body has a radius of 20 cm and a height of 15 cm. The max power of actuators is of 1 Watt, the max torque is of 1 N m, the number of actuators per end-effector is one, the number of the total actuators is twelve, the capacity of the battery is of 20 thousand mAh at the voltage is of 5V (valued consumption is of 0.2 J/sec, autonomy is 100 hours). The proposed TORVEastro configuration has the possibility to have symmetric three-link and the robot can be used with any posture that can be easily maintained because of a modular design with interchangeable parts. The end-effector can act either as a foot or as a gripper (fig. 1). Each link of the service robot consists of a 2.5-1 mm thick hollow cylinder with a circular cross-section arc of radius of 20 cm and an angular opening of 80 $^\circ$ (fig. 2). Inside the link there is the possibility to pass the necessary wires of the sensors. The fig. 3 shows how the servomotors are positioned inside the central body. The Central Servomotor (CS) controls the rotation of $\theta_1$ by a drive motor shaft, the Left Servomotor (LS) controls the rotation of $\theta_2$ through a pair in mechanical tension wires. Finally, the Right Servomotor (RS) controls, through mechanical tension wires, the opening and closing of the arm 2 through a free disk wheel to rotate compared to the joint 2 and linked with another wheel fixed in the joint 3 (fig. 3). The connection between the links and the joints is designed according to have a symmetric geometry in order to have a proper balance of the masses compared to the link axis.
Figure 2. A CAD model for mechanical design of TORVEastro in fig. 1:
  a) Full open configuration; b) Full closed configuration.

Figure 3. Connection between servo-motors and joints by wires in fig. 2:
  a) Internal position of the servomotors;  b) Link between RS and the joint 3.

4. Performance evaluation
A space robot must have the ability to walk and simultaneously manipulate objects. In the walking mode TORVEastro moves by using grasp while the third foot does not participate to the walking and it can do some other tasks. In order to characterize the motion of the robot, simulations have been computed in SolidWorks with the characteristics data of micro gravity at 0.1 g to simulate micro gravity in the space and in addition there are low value of friction (because bearings are used to transform friction and sliding into rolling friction) and low damping area is assumed at the joints of robot mechanical design. In the first step, TORVEastro capability to move in the space environment has been evaluated by the using of the Torque Motor 1 (TM1), shown in fig. 3 as a central servomotor, it is able to produce a rotation in 01. Velocity, angular velocity and acceleration of the end-effector are evaluated by the using of TM1. Reaction forces and moment are evaluated in each rotary joint with result in fig. 5. TM1 is used for a variable time of some seconds and its value (TM1) has a cubic pattern as a function of time operating by a maximum value of 1N m and a minimum value of -0,5 N m. In this motion mode TORVEastro is able to perform a rotation of $2\pi$ rad in 2.40 s. The maximum
value of reaction force is of 9 N and the maximum value of the reaction moment is of 9.6 N m. The joints with largest reactions are joint 1 and joint 2 of link11. The simulation results show very slow value of joint reaction and proper value of mobility, due to the lightweight design of the space robot. A wide range of values were analysed during the simulations of performance evaluation. The simulations were evaluated by the use of:

- Torque motor 1 (TM1);
- Torque motor 2 (TM2);
- Torque motor 3 (TM3);
- TM1+TM2;
- TM1+TM2+TM3.

The most critical situation in terms of relative speeds, accelerations and constraint reactions, it was shown during the simulation in which 1-2-3 actuators were used simultaneously as reported in fig. 5-6. TM1, TM2 and TM3 have a cubic pattern as a function of time. In this configuration the end-effector has reached the max value of velocity of 2.4 m s\(^{-1}\) and the max value of angular velocity compared to the joint 1 of 9.45 rad s\(^{-1}\), the max value of linear acceleration has been of 15 m s\(^{-2}\) (fig. 7). The max value of reaction force has been of 11 N and the max value of reaction moment has been of 4.6 N m. The simulation results show a proper ability to move of TORVEastro. The kinematic analysis shows values and time histories that demonstrate the feasibility of this space robot for a practical implementation in service objectives in space stations. The constraint reactions show values that demonstrate solidity of the joint of the robot.

![Figure 4](image)

**Figure 4.** Plot of numerical results of the simulation:

a) Position of center of mass of end-effector (x, y, z components); b) Velocity and angular velocity of center of mass of end-effector; c) Linear acceleration of center of mass of end-effector.
The links of the space robot have been studied by FEA (Finite Element Analysis) subjecting the end-effector to a load of 100 N. Assuming that the element size used for meshing an entity is \( e \), the average element size in layers radiating from the entity will be: \( e, e \cdot r, e \cdot r^2, e \cdot r^3, \ldots, e \cdot r^n \) (\( e \) is the element growth ratio). If the calculated average element size of a layer exceeds \( E \), where \( E \) is 3.21 mm the program uses \( E \) instead. The mesh radiates from vertices to edges, from edges to faces, from faces to components, and from a component to connected components (fig. 6). In the fig. 7 the red arrow represents the yield strength of the material. After several studies the thick of the two links of the robot is 2.5 mm for link1 and 1mm for link2 and, as shown in fig. 7, this configuration has the possibility to support the load of 100 N.

---

**Figure 5.** Plot of numerical results of the simulation:
- a) Max values of reaction force;
- b) Max values of reaction moment.

---

**Figure 6.** Mesh density:
- a) Mesh density of joint 1;
- b) Mesh density of joint 2.
Figure 7. Plot of results of FEA analysis:
  a) Tick of link1 and link2 is 1 mm; b) Tick of link1 is 2.5 mm and tick of link2 is 1 mm.

5. Conclusions
TORVEastro robot is proposed and simulated for service applications to help astronauts to do assembling and to do some other tasks like repairing and monitoring works outside space orbital stations.

The proposed conceptual kinematic design is obtained as a result from an analysis of operation problems and requirements in space. The robot design is composed of one central body and three legs/arms with the purpose to have robust, versatile, compact, and light design. Simulations have been used to characterize the mobility performance to give first indications for a feasible design of a first prototype. Future work is planned for experimental validation and performance testing.

References
[1] Sun Z, Li H and Ceccarelli M 2018 Prototype Design and Performance Tests of Beijing Astronaut Robot, Applied Science
[2] Kawamura K, Rogers T E, Hambuchen K A and Erol D 2015 Toward a Human–Robot Symbiotic System, Household Service Robotics
[3] Michalos G, Makris S, Tsarouchi P, Guasch T, Kontovrakis D and Chryssolouris G 2015 Design considerations for safe human-robot collaborative workplaces, Procedia CIRP 37 248–253
[4] IFR, International Federation of Robotics, https://ifr.org/
[5] ISO 8373:2012, Robots and robotic devices, https://www.iso.org/standard/55890.html
[6] Csorba K, Varga D, Tevesz G and Vajk I 2012 The RobonAUT autonomous mobile robot construction contest?, IFAC Proc. 9(1) 360–365
[7] Christoph B, Wimböck T, Schmidt F, Fuchs M, Brunner B, et. al. 2009 Rollin' Justin - Mobile Platform with Variable Base, IEEE International Conference on Robotics and Automation
[8] Bogos S 2013 Kirobo Will be Japan's First Robot Astronaut, http://www.escapistmagazine.com/news/view/125525
[9] Calderone L and Matthews K 2014 Robot Astronaut 'Kirobo' Ready for Launch to International Space Station, Robotics Tomorrow
[10] Yoshida K and Wilcox B 2008 Space Robots and Systems, Springer Handbook of Robotics 1031-1063
[11] Lambright W H 2019 Administrative Leadership and Long-Term Technology: NASA and the International Space Station, *Space Policy* 47 85–93

[12] Hoppenbrouwers T, Ferra L, Markus M and Wolff M 2017 Acta Astronautica Operations Data Files, driving force behind International Space Station operations, *Acta Astronaut.* 138(May) 255–261

[13] Thuot P J and Harbaugh G J 1995 Extravehicular activity training and hardware design consideration, *Acta Astronaut.* 36(1) 13–26

[14] Ceccarelli M, Li H, Carbone G and Huang Q 2015 Conceptual kinematic design and performance evaluation of a chameleon-like service robot for space stations, *Int. J. Adv. Robot. Syst.* 12