Doctoral Dissertation
Doctoral Program in Mechanical Engineering (35^{th}cycle)

An Inflatable Robotic Manipulator for Space Applications

By

Pierpaolo Palmieri

******

Supervisor(s):
Prof. Stefano Mauro

Doctoral Examination Committee:
Prof. Benedetto Allotta, Referee, Università degli Studi di Firenze
Prof. Pierluigi Beomonte Zobel, Referee, Università degli Studi de L'Aquila

Politecnico di Torino
2023

An Inflatable Robotic Manipulator for Space Applications

Pierpaolo Palmieri

The rapid growth of the space sector encourages the research of cost-effective solutions to execute an increasing number of missions. Specifically, in-space servicing, assembly and manufacturing (ISAM) and active debris removal (ADR) activities require advanced robotic systems, capable of performing complex tasks, such as maintenance of satellites or assembly and construction of large and complex space structures. This work introduces a novel deployable and lightweight robotic manipulator with inflatable links for space applications. This system can be stored in a relatively small volume and deployed when required. It can be withdrawn when its employment is not needed. This solution allows to limit the manipulator weight and size at launch, aiming to reduce costs. The hybrid architecture, which integrates rigid joints with conventional electrical actuation, enables the application of standard control methods for the robot. This work offers design procedures and models for the development of the robotic arm, with particular focus on the critical load conditions which cause the appearance of wrinkles and the structure collapse. Candidate materials suitable for space are discussed, underlining the necessity of high tensile strength capabilities for the inflatable links. The theoretical background regarding inflatable structures is applied for the development of models for the inflatable robotic arm, useful for design and simulation purposes. Two dynamic models for robot are examined to account for link flexible behavior: one introduces virtual joints following a lumped-parameter approach and the other one uses finite elements according to the Euler-Bernoulli theory. A robot prototype for laboratory testing has been developed, validating the concept, after analyses run on inflatable link prototypes. In the current development phase, the robot can be controlled using teleoperation, enabling future implementation of advanced automatic controls. Different control techniques are proposed, identifying in visual servoing the key methodology to perform accurate positioning of the robot. Finally, the proposed vision-based control algorithms are integrated in a virtual environment, using the developed dynamic models. The first simulation represents the prototype reaching a target using the model based on virtual joints validating the visual servoing. Then, a space application is simulated: a large-size inflatable robot is mounted on a spacecraft and correctly grasps a space

debris recurring to visual servoing strategies. This work demonstrates the feasibility of the proposed technology, defining design and modeling methods, developing the proof-of-concept, identifying suitable control strategies and providing virtual simulations of the system. Further steps, aimed to enhance the technology readiness level, are identified in the development, testing and validation of a new prototype with suitable space materials and in relevant environment.