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A modular cable robot for inspection and light manipulation on celestial bodies

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ABSTRACT

Planetary exploration has been carried out with solitary probes since the nineteen-sixties; on the other hand, the newly emerging paradigm for robotic exploration shows multi-expertize, complex modular systems as necessary for efficient and thorough activities. In this paper we propose a modular Cable Driven Parallel Robot (CDPR) that is deployed by a rover, which can take advantage of its large workspace for tasks as inspection or light manipulation. While the general deployment procedure is described, focus is given on the CDPR; a model for the pseudostatics of the robot is formulated, as well as an analysis on its modules stability. The workspace is then characterized using appropriate metrics. Results show that a 1 Kg payload for the end-effector is effectively feasible with substantial margin for an equilateral triangular workspace of 10 m side. Finally, several possible practical applications are illustrated.

1. Introduction

The exploration of planets and other celestial bodies has been, up to this point in history, carried out by the use of small, solitary, one-package probes [1,2]. Since the first soft landing performed by the Soviet's Luna 9 in 1966 on the Moon, many landers have been deployed all around the solar system, e.g. Mars [3], Venus, even Jupiter's moon Titan with ESA's Huygens probe [4] in 2005, or, more recently, the partially successful landing of ESA's probe Philae [5] on comet 67P/Churyumov–Gerasimenko. A subset of these probes are the so-called rovers, robotic vehicles designed to travel across the surface of planets or, more generally, unexplored, and possibly hostile, environments. Notable examples are Lunokhod 1, deployed on the moon in 1970, which kept operating for 11 months, the mars rovers MER-A and MER-B, the latter still in operation after more than 11 years from its landing, and finally the most recent Mars Science Laboratory (MSL) rover [6]. Future planned rovers include ISRO's Chandrayaan-2 [7], ESA's ExoMars [8] and Mars 2020 Rover Mission from NASA [9]. As it is clear from reviewing all these missions, the focus is on the scientific payload that is on-board the rover. This calls the robot to be conceived primarily as a mobility and support structure for the several instruments that need to probe the environment in different locations. This rationale results in a system that needs to be as self-contained as possible, to be efficient and to save weight. A partial deviation in principle is represented by landers made by an autonomous base and a rover. An example is NASA's Sojourner, part of the Mars Pathfinder mission [10], in 1996–7, or the recent Chang'e 3, with its partially successful rover Yutu [11], in 2013.

The design of rovers has thus been geared towards mere carriers of scientific instruments. Indeed, modularity in its broad sense has seen, up to now, extremely limited practical development in the field of space exploration, mainly for the mentioned lack of necessity. In the last decade, though, with the prospect of entering into a new phase of exploration – especially of Mars and the Moon – a new paradigm is starting to take form [12–14]; one where rovers and robots are not simple carriers, but actually constitute and support a modular, multi-expertize environment for complex planetary activities that can go from sample extraction, collection and processing, to the preparation of a base for manned exploration or resource gathering [13–21].

Despite the lack of an implementation in the real space environment, there is ongoing development on the subject of integrated robotic exploration; for example, Fink et al. [22] describe a framework for the robotic exploration of lava tubes of which there is strong evidence both on the Moon and on Mars.

Cordes et al., with the LUNARES project [24], describe the development of a framework for collaborative robotics with the intent of lunar craters exploration; static, wheeled, and legged robots are implemented.

Modular robotics applied to celestial bodies exploration has

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been also investigated by the RIMRES [24] and ROBEX [25] projects, which describes the collaborative operations of several heterogeneous autonomous robots. In particular, a wheeled rover with a serial manipulator is used to load, carry to target and deploy immovable modules on the ground that can contain scientific instrumentation, experiments or other devices like radio beacons.

A supervised autonomy tele-robotics experiment [26] under the METERON project demonstrated the use of the DLR's (Deutsches Zentrum für Luft und Raumfahrt) wheeled anthropomorphous robot Justin, for the maintenance of a solar array deployed in a space environment.

Cable Driven Parallel Robots (CDPRs) form a class of robots that exploit tethered mechanisms to manipulate the end-effector; in particular, the end-effector is suspended with cables and a coordinated system of winches handles the actuation, by varying the lengths of unwound cable. In general it is a well-known research subject, and extensive work has been performed over the years, as seen from [27–34]. An aspect which has seen comparatively low attention is that of sagging cables; the general trend is to approximate the tethers as negligible-mass components. Indeed, very few works have addressed sag by modeling cables as catenary curves [28,33,34].

With a few notable exceptions, CDPRs have seen poor implementation in the space environment; perhaps the best example is the NIST Robocrane, described by Roger et al. in 1993 [30].

Conversely, a topic which is very well developed in the space industry context is that of tethered systems, particularly orbital, as described in [35,36] or [32].

In this paper, we present a novel application of cooperative and modular robotics to the field of space exploration. This consists in a series of 3 modules that, when deployed, constitute a 3-links Cable Driven Parallel Robot (CDPR) that can perform efficiently tasks which require a large workspace and a lightweight structure. The modules themselves are arranged and deployed by a rover equipped with a serial manipulator with a docking interface instead of a conventional gripper.

In Section 2, the system is described in detail: the module, the end-effector and the deployment procedure are illustrated in depth. In Section 3 a complete pseudostatic model of the robot is presented; the stability of the modules is studied with the aid of the stability polytopes, and the groundwork for the characterization of the workspace is illustrated. In Section 4 the results of the analysis are reported and discussed, while in Section 5 a thorough analysis on possible applications is described.

2. Description of the system

The system consists of 3 types of components: the modules, the rover and the end-effector. Initially, these are separate and possibly stowed. The deployment process consists of positioning the 3 modules, and connecting the end-effector to the cables attached to each module; this procedure is carried out by the rover.

The CDPR, as mentioned in the introduction, consists in the 3 deployed modules, which provide the active winches that operate the cables. In the following subsections the module and the end-effector subsystems are presented. Finally, the deployment procedure is outlined, along with a general description of the rover.

2.1. The module

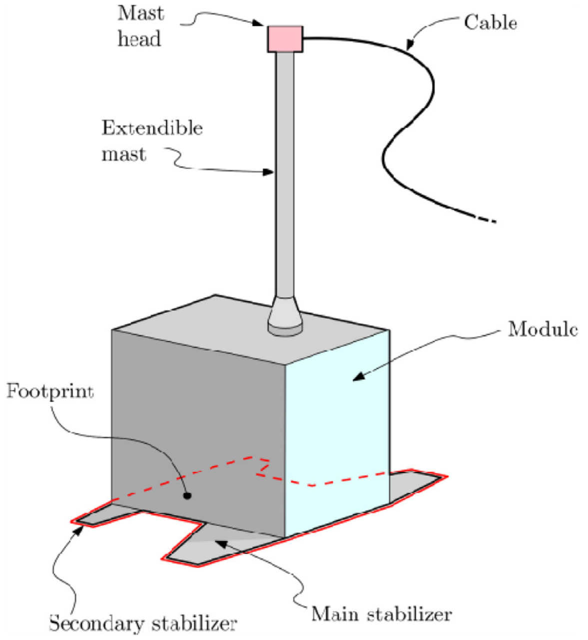

Fig. 1. A module of the 3-cable CDPR robot. The prism at the bottom contains the actuator for the extendible mast and the control system. The main and secondary stabilizers are illustrated at the very bottom, and the footprint is highlighted.

Each base module, as seen in Fig. 1, is a device which must be stable on rough terrain, provide structural integrity to the system, and perform its hardware control functions. In this work we focus on a module which is not fixed to the ground, but simply lies on top of it, relying on friction with the ground to keep its position.

In order to coordinate the feed of the cables, a master-slaves configuration is advisable, where one module acts as the master, and the rest as its slaves; the master module provides all of the high-level functions, e.g. path-planning, vision, communication with the slaves, etc., whereas the slaves themselves will perform the lower-level functions, i.e. control of the winches, relative position control, etc.

Since the module is not fixed to the ground, a fundamental characteristic of it is its footprint, since it contributes to its stability when loads are applied by the cables. In this paper we discuss three different types; by looking at Fig. 1, one can see that two pairs of stabilizers exist, the "Main" and the "Secondary stabilizer". These are lightweight deployable structures that widen the footprint of the module, thus making it less prone to tilting and ultimately toppling. We call "A" the situation where no stabilizer is present, "B" where only the main ones are deployed, and "C" where both the main and the secondary are open. It is worth noting that the stabilizers are placed only on the side of the module and not, for example, on the front; the rationale is that the module is comparably thin, so the stabilizers are placed to compensate the poor stability in the transversal direction.

The power-requirements of each modules are, for the purpose of this paper, based on the winches used for the cables. Considering a maximum speed of 0.5ms^{-1}, and a mass of 1Kg on the end-effector, this translates into approximately 5 W, relative to the worst possible load condition, in Earth gravity. Considering all possible losses, this figure could easily grow to 10/50 W.

2.2. The end-effector

The end-effector that we propose as an example in Fig. 2, consists of a body frame on which a pan-tilt camera is mounted. Since the component must be allowed to be disconnected from the cables, a docking system is employed for the connection. Since the cables should incorporate data and power transmission functions, the docking adapters must employ a coaxial connector.

In general, the only major limitation on the characteristics of end-effector is weight, as will become evident in the following