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Inertia parameters identification for cellular space robot through interaction

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ABSTRACT

Most of the technologies are in high-speed evolution nowadays. But the spacecraft, however, is still high-priced and takes years to construct. Besides that, it is hardly to service since the conventional spacecraft are not serviceable designed. Facing those challenges, the concept of cellular space robot is presented in this paper for both spacecraft system construction and on-orbit service. As a typical on-orbit service task, the non-cooperative target takeover control is considered in this paper. Specifically, the /colorreviseinertia/colorblack parameters identification for takeover control is studied in this paper. Because the cells in the cellular space robot are interconnected and networked, an /colorreviseinteractive/ colorrevise parameter identification algorithm is presented to solve the parameter identification problem by cells interaction. The algorithm is distributed and both synchronous and asynchronous interaction are supported. The algorithm is validated and analyzed by numerical simulations.

1. Introduction

Spacecraft, especially the satellites are widely used in various fields and greatly facilitate our everyday life in different ways. With the developing of space technologies, the annual launch number of spacecraft grows enormously to meet the increasing demands. However, unlike the other technologies whose cost falls sharply after its /colorrevise inception /colorblack, the cost of the satellite has not been reduced for decades despite the development of the fundamental technologies. One of the major reasons is that a lot of testing is required during the spacecraft development in the conventional way. The heavy testing is not only costly but also time-consuming. Conventional construction of a big satellite takes 3 to 5 years, while nearly half of the time is consumed for testing [1]. Thanks to the development of small satellites like CubeSat, 94% of them built by commercial and military entities will only take 24 months [2,3]. Even so, it is not enough for emergency response. Besides that, since the emergent of the satellite, its morphology has not changed [4]. The spacecraft nowadays are monolithic and as a consequence, the spacecraft with higher performance mostly have a greater mass. For a space mission, mass is a proxy of the cost, therefore, the monolithic morphology hinders the search of a lower cost solution.

On the other hand, on-orbit service and debris removing are attractive fields nowadays [5], but the monolithic design also makes the spacecraft unrealizable for function adjustment which is considerably necessary for emergency response. Meanwhile, the conventional spacecraft without service-friendly design can hardly provide facilities for on-orbit service. Although the space manipulator is considered the most promising technique for on-orbit service [6–8] and maintenance, it is impractical to design a universal space manipulator to fit all diverse structures of heterogeneous spacecraft considering the variety of the spacecraft. On the other way, it is too costly and time-consuming to construct a specialized space manipulator for each mission.

Therefore, it is difficult to reduce the costs or shorten the development cycle of a satellite without changing the conventional design pattern [9]. And also, trying to enable the flexible function adjustment without changing the morphology is a huge challenge.

To overcome the above-mentioned problems, a new design pattern of the spacecraft by breaking down the monolithic morphology is proposed. That comes to the concept of cellularied design.

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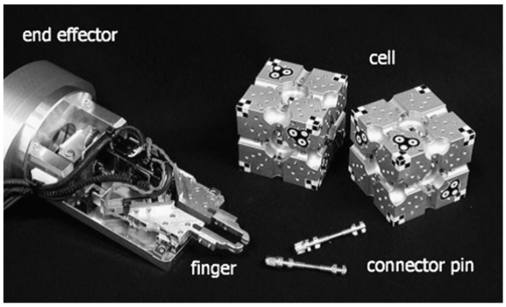

Fig. 1. Prototype of the CellSat [10].

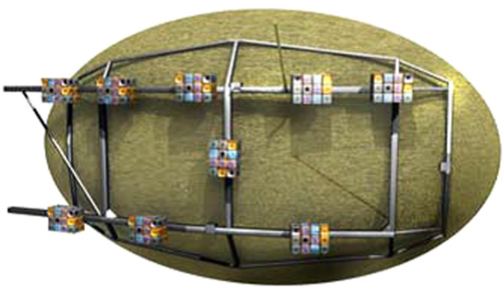

Fig. 2. Concept of DARPA's Phoenix [12].

Cellular Space Robot (CSR) is a cellularized design that provides a new approach for both spacecraft construction and space operation. By disaggregating the architecture of the spacecraft according to the subsystem function (e.g. sensing, communication, attitude control, etc.), we can get different kinds of architectural units. Each architectural unit is physical independent, functional independent and equipped with standardized structure and standardized interface. Aggregating the units together brings out a full functional spacecraft system. The independence and standardization of the cells conduce to the functional flexibility and configuration flexibility of the aggregation system. The aggregation system has a morphology architecture similar to the biological organization of the multicellular species. Each architectural unit can be regarded as a cell of the aggregation system, and hence comes the name of cellular space robot.

The concept of cellular space robot proposed in this paper is on the foundation of other researchers' significant work. The CellSat as shown in Fig. 1 is a cellularized satellite proposed by Hideyuki Tanaka and Noritaka Yamamoto [10,11]. The CellSat includes the cells and connector pin, and the system is maintained by a specialized space manipulator. Hideyuki Tanaka and Noritaka Yamamoto also built a prototype and studied the accurate assembly by the manipulator [10]. In consideration of the advantage in rapid response of the cellularization. Several organizations have proposed their research program on it. DARPA presented the Phoenix program [12–15] to harvest the antenna of the retired satellites and aggregate the cells named "satlets" [15–17] with the antenna to build a new satellite. The concept of the Phoenix program is shown in Fig. 2. With the help of the space manipulator FREND, the new satellite might be built in situ rather than launched from the ground. The iBOSS [18,19] (Intelligent Building Blocks for On-orbit-Satellite Servicing) is another cellularized spacecraft to facilitate the on-orbit service and maintenance, as shown in Fig. 3. The standardized "building blocks" can be easily replaced on orbit and that releases the need of the manipulation skills. As a conclusion, a specialized space robot is needed in the projects mentioned above, for example the FREND in the Phoenix program.

Meanwhile, the cellularized design system can be easily manipulated because of its standardization. Owing to that, a simple

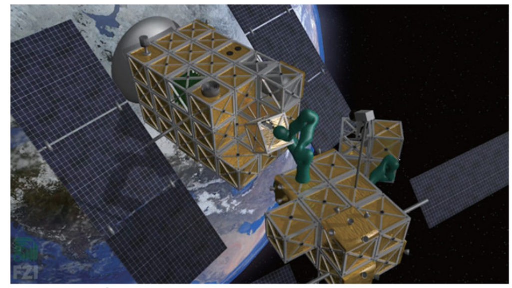

Fig. 3. Concept of DLR's iBOSS [18,19].

mechanism named manipulation cell can substitute for the manipulator to manipulate the cells. The system can manipulate the cells and execute various manipulations with help of the manipulation cells and end effectors. Hence, the cellular space robot is capable of self-maintenance and servicing the other spacecraft. Such a system can be implemented as both conventional spacecraft and space robot. That is the connotation of the Cellular Space Robot. As reported, a lot of the high valued spacecraft reach their end of life unexpectedly due to the propellant depletion or control system malfunctions [20]. However, the valuable payloads onboard are still functional. Therefore, there is an urgent need for on-orbit service to restore the control capability or replenish consumables. To accomplish the on-orbit service, the target should be captured first. Besides the conventional space manipulators, a lot of capturing methods including tethered space robot [21–23] and maneuverable tethered space net [24,25]. After capturing the target, many servicing tasks can be implemented. Among them the takeover control [26–28] offers a feasible solution to extend the working life of the spacecraft with propellant depletion or control system malfunctions. The OLEV (including CX-OLEV [29] and SMART-OLEV [30]), SUMO [31,32] and Orbital ATK MEV [33] are representative projects focus on spacecraft life extension. By attaching on the target spacecraft the service spacecraft provide a fully functional substitute for the original control system, allowing the remaining payloads to perform normally. While attaching to the target spacecraft to service, the cellular space robot can take over the attitude control system of the target and restore the control capability. The cells attached on the target constitute the proxy control system. Moreover, thanks to the flexibility of the cellular space robot, it suits more target spacecraft by adjusting amount and configuration of the cells.

Since the target spacecraft on orbit nowadays are not service-friendly designed, i.e. the target spacecraft are non-cooperative. The parameters, especially the inertia parameters which are crucial to takeover control are unavailable. Consequently, the dynamic parameters identification is the primary problem for the takeover control. Moreover, the inertia parameters identification is also essential for self-reconfiguration of the cellular space robot since the switch of the system configuration might lead to change of the parameters. The topics of the inertia parameter identification for space manipulator [34], tethered space robot [35] and conventional satellite are widely researched, there are summarily two types of methods: the method based on Newton–Euler method [36–38] and the method based on the law of conservation of momentum [34,39].

The takeover control scenario of the cellular space robot indicates that multiple cells are needed because the ability of a single cell is not sufficient to drive a target spacecraft with much greater mass. The cells attached on the target spacecraft have to work in coordination. The cells can interact with each other via the data interface and hence the configuration of the aggregated system is networked and each cell can be regarded as a node in the network. As a consequence, the model identification for the cellular

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