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# Dynamics and robust adaptive control of a deployable boom for a space probe

ZhongYi Chu [1], YiAn Lei *, Dan Li

*Science and Technology on Inertial Laboratory, Beihang University, XueYuan Road, 100191 Beijing, China*

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ABSTRACT

Various spacecraft missions have driven the need for lighter, stronger deployable structures, which help to hold instruments, such as a magnetometer, away from the spacecraft to avoid the disturbance caused by remanence of the spacecraft body. In this paper, we will present a type of deployable boom for small spacecraft, which is characterised by a small stowed volume, light weight and a large magnification ratio. Because the actual parameters of the deployable boom are all nonlinear, modelling of the boom becomes a key point. Considering the uncertainties in the model parameters, an approximate dynamic model with uncertain parameters is formulated by classifying the uncertainties into different types, including constant parametric, variable parametric and nonparametric uncertainties. Then, a robust adaptive control strategy is proposed to compensate for or reject these uncertainties separately; a feed-forward and feedback controller is designed to reduce the errors between the desired and the real trajectories, an adaptive controller aims at compensating for constant parametric uncertainties and a robust controller is used to reject the variable parametric and nonparametric model uncertainties. Thus, a robust adaptive control strategy does not rely on the exact dynamic model and can completely compensate for or reject the effect of model uncertainties. Finally, the simulation results show that the proposed control law is perfectly adequate for the deployable boom.



## 1. Introduction

Deployable structures were first proposed by NASA in the 1960s and play an important role in space missions by holding instruments, such as a magnetometer, away from the spacecraft. Bowden broadly classified these devices into hinged, linear, surface and volume deployable devices [1]. Among these groups, the linear deployed boom is the simplest and most frequently used, such as in telescoping, inflatable, articulated or coiled, and tubular extendable booms [2]. As shown in Fig. 1, the tubular extendable booms (including the STEM and BI-STEM) are the most popular and have been commercially available for decades [3]. NASA proposed an 18-m-long lenticular deployable boom for the space shuttle, a collapsible rollable tube (CRT) mechanism for reconfigurable small spacecraft [1] and an instrument deployable mechanism for the THEMIS satellite [4]. Roybal from New Mexico, United States made a triangular retractable and collapsible (TRAC) deployable boom, which has a triangular cross section [5,6]. The German aerospace centre (DLR) also successfully developed a $5 \times 5$ m solar-sail deployable mechanism that includes four cross-shaped lenticular booms [7,8]. Recently, a more advanced lenticular boom has become popular; this boom is usually made of carbon fibre reinforced plastic (CFRP) or other composite materials and can be stowed on reels by changing from a flattened to a curved

* Corresponding author. Tel.: +86 15010274633; fax: +86 010 82339013.
*E-mail addresses:* chuzy@buaa.edu.cn (Z. Chu), leiyian2007@126.com (Y. Lei).
[1] Tel.: +86 13552712797.

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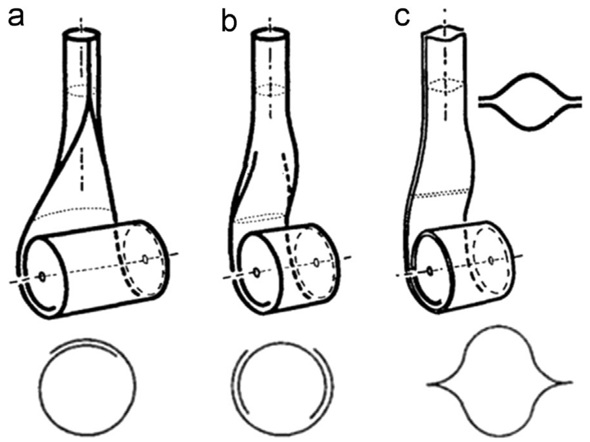


**Fig. 1.** Different tubular extendable booms: (a) stem; (b) bi-stem; and (c) lenticular boom.

geometry. Although the aforementioned deployable booms have different styles and structures, they are all based on careful design. Regarding aspects of designing deployable booms, Hakkak used certain shell theories [9–11] to confirm the preliminary parameters of the boom, which are the foundation of later precise designs [2]. Warren confirmed the designed parameters using the finite-element method, which is more accurate and credible [12]. Later, Rehnmark designed a precise deployable mechanism using CAD software [1]. However, to satisfy the requirements of a specific space probe task, some given constrains and requirements must be considered in the process of designing deployable booms, such as the volume (both stowed and deployed), weight, natural frequency, bending and torsional stiffness of the boom.

As for the modelling of the deployable boom, researchers usually build a second-order differential dynamic equation using the Lagrange method for the entire system. However, many parameters in the dynamic equation are nonlinear in practice and a math model with constant parameters cannot be adopted; therefore, extensive efforts have been exerted to build a more accurate nonlinear model. Rehnmark built a nonlinear math model of the reaction springs, which are a key component in a deployable boom [1]. Furthermore, because friction compensation is very important for mechanical systems [13], Armstrong provided a detailed survey of the friction model [14]. Although a significant effort was made to build a more accurate model, researchers were obliged to pursue an appropriate control compensator because of the unavoidable existence of model parameter uncertainties [15].

Many control laws have been proposed for similar booms. The most common one is the PID controller, which is very useful when the dynamic model is basic linear or time invariant but is not suitable when dealing with the problem of parametric uncertainties. To solve the problem, an adaptive controller must usually be used. However, it should be pointed out that the dynamic model of the deployable boom cannot be linearly parameterised, and therefore, an adaptive controller using a linearly parameterised model cannot be used directly. To overcome this difficulty, Parlaktuna proposed a joint space adaptive tracking control scheme with an online parameter identification process [16]. Seok developed a control strategy using an adaptive predictive controller with a notch filter [17]. However, usually these adaptive schemes can only handle parametric uncertainties, that is, the effect of nonparametric model uncertainties cannot be rejected. To address this problem, a robust controller is a necessary complement; such a controller can reject the nonparametric model uncertainty by considering the boundaries of the parameters. Song proposed a robust controller to compensate for the uncertain friction [18], Chang designed a robust controller to track an uncertain electrically driven robot [19], and Jin developed a robust control law for a robot boom with nonlinear friction by using time-delay estimation [20]. However, the robust controller has its own conservative characteristic; in practice, we usually do not know the exact boundaries of the parameters, and as a result, the control performance decreases. Thus, an artificial neural networks (ANNs)-based adaptive control law was developed by Chaoui, which was extremely efficient [21]. However, computational complexity becomes a problem when controlling a deployable boom in the space probe environment.

This paper presents the design, modelling and control of a deployable boom that is characterised by a small stowed volume, light weight and a large magnification ratio. Firstly, we design a deployable boom for small spacecraft based on material theories and the finite-element method. Secondly, an approximate dynamic model with uncertain parameters is established. Then, to completely compensate for or reject these uncertainties, we classify the uncertainties into three types: constant parametric, variable parametric and nonparametric model uncertainties. Finally, a robust adaptive control strategy is proposed to address all the uncertainties. A feed-forward and feedback controller is designed to reduce the primary errors between the desired and the real trajectories, and then an adaptive controller is proposed to compensate for the constant parametric uncertainties with the goal of further reducing errors. Additionally, a robust controller is developed to improve performance by rejecting other variable parametric and nonparametric model uncertainties, and all the controllers cooperate with each other in tracking the desired trajectories. The controllers do not only rely on an exact dynamic model and can completely reject or suppress uncertainties caused by model parameters and nonparametric parts. In conclusion, the simulation results validate the proposed controller.

This paper consists of six sections, and the rest of the paper is organised as follows. In Section 2, the design of the deployable boom is presented. In Section 3, the dynamic model formulation and uncertainty analysis are developed. Then, the control strategy and its stability proof are proposed in Section 4. Computer simulations are shown in Section 5. Finally, the conclusions are given in Section 6.

## 2. Design of the deployable boom

### 2.1. Brief view

As shown in Fig. 2, the designed deployable boom consists of three parts: the storage part, the transmission