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Overview of Spacecraft Mechanisms and Actuators and their Associated Applications

1.0 Abstract

Spacecraft mechanisms are integral to spacecraft design, they are used in tasks such as deploying components of the spacecraft, pointing instruments, and releasing the spacecraft from the launch vehicle. This paper aims to provide an overview of these applications and some solutions to the design problems provided by operating in the space environment. Understanding the breadth of mechanisms and their associated actuators is important for bringing creative solutions to the spacecraft design.

2.0 Intro

The space environment offers unique challenges to spacecraft designers regarding the release, deployment, and operations of spacecraft. The lack of human involvement in physically configuring the spacecraft after its launch coupled with the harsh conditions the spacecraft will encounter on orbit lead to a plethora of mechanisms and actuators each adapted to their specific application. Despite this there are some attempts to sort mechanisms by type. Smad organizes these into three important categories based on function: deployables, drives, and instrument mechanisms. While Nasa recognizes four categories: pointing, manipulating, deploying, releasing [2]. No categorization is perfect however; for instance, neither of these categorizations capture thermal control actuators, or propulsive actuators for that matter. For the purposes of this paper I will limit my scope to the following types of mechanisms and their associated actuators: release mechanisms, deployable booms, and gimbals. This limit on scope is simply because they are of most interest to my ongoing research for my spacecraft design course.

3.0 Literature - Examples and Applications

In this section I will look at examples, applications, and considerations for the three types of mechanisms that I have selected. In all cases this is a preliminary look, intended to help highlight some of the considerations, without exhaustively looking at all potential solutions to these actuation problems.

3.1 Release

Perhaps the most universal mechanism for spacecraft is release mechanisms. Regardless of the spacecraft's mission, mass, complexity, or cost, the spacecraft must be released from its launch vehicle autonomously The most traditional type of release mechanism is the “Marman” clamp [3]. It is nicknamed after the company who originally developed the clamp as a generic way to attach cylindrical segments together. The clamp is a band of metal similar to a pipe clamp, formed in such a way that its cross section will capture flanges on the cylinders which it aims to connect Fig. 1. The cylinders are connected by tensioning the clamp which, again much like a pipe clamp, and are later released by releasing the tension in the clamp.

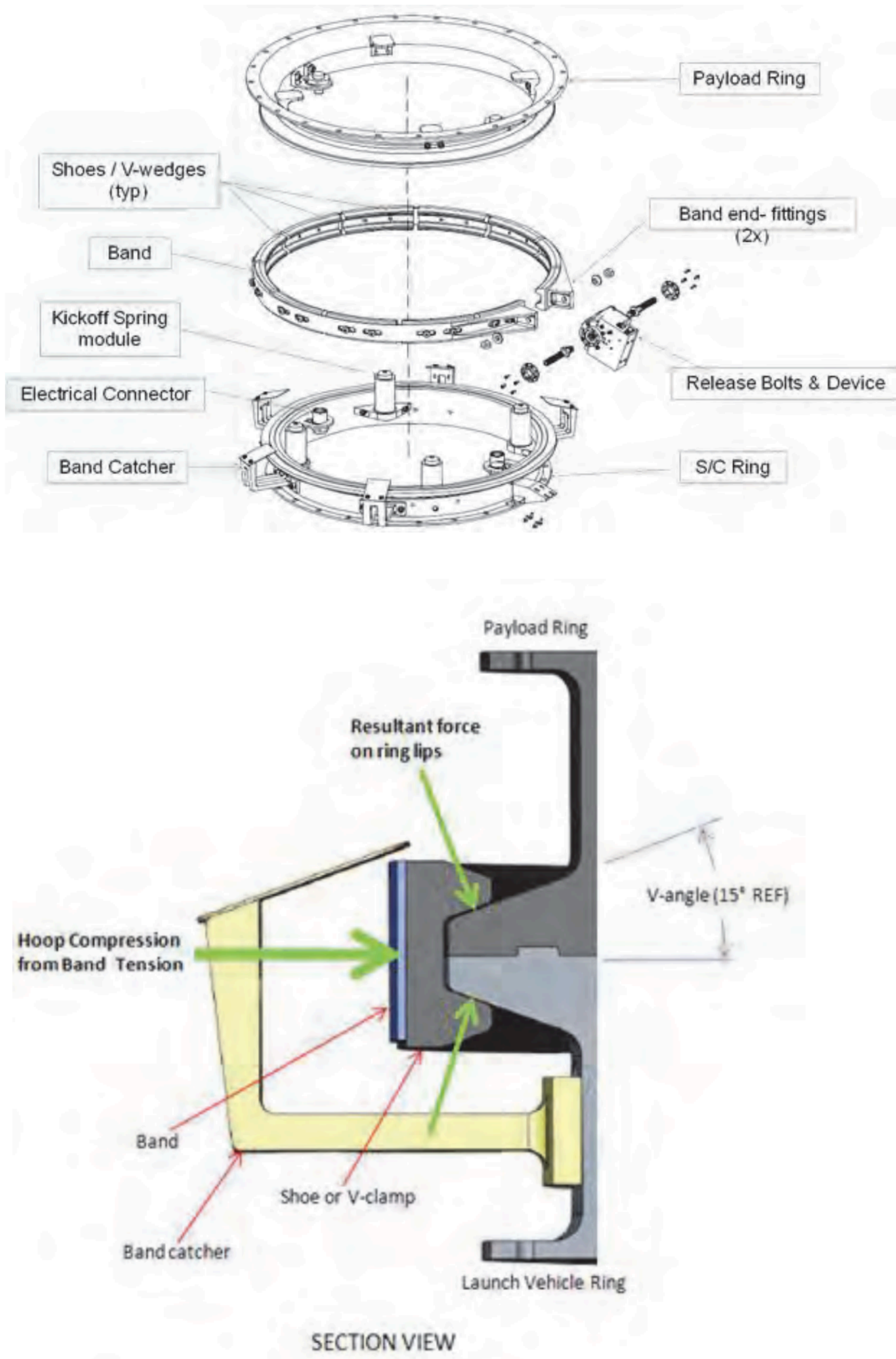

Fig.1 [3]

This release of tension is historically achieved with the help of an explosive bolt, which can be detonated to inflight to release the tension in the clamp [3]. These come with a significant disadvantage however.

The explosion of the bolt creates significant shocks in the spacecraft which have the potential to damage the spacecraft [4]. In addition to this, there is debris generated from the detonation of the bolt that could lead to contamination of other parts of the spacecraft. This would be especially risky to the mission if the contamination found its way to a delicate part of the spacecraft such as the payload.

An alternative to explosive bolts is the aptly named non-explosive bolt. The most prevalent of these is the Frangibolt. It operates using the expansion of a Shape Memory Alloy (SMA) such as Nitinol. Nitinol is a Nickel Titanium alloy (hence the name) and has the special property that if plastically deformed at room temperature, and then heated, it will return to its original shape. This property is used in a Frangibolt to The Frangibolt consists of a cylindrical piece of SMA and a heater. The SMA expands when heated and exerts a tremendous amount of pressure on the bolt head which causes the bolt to fracture. It has the advantage of generating much less shock than an explosive bolt and less debris.

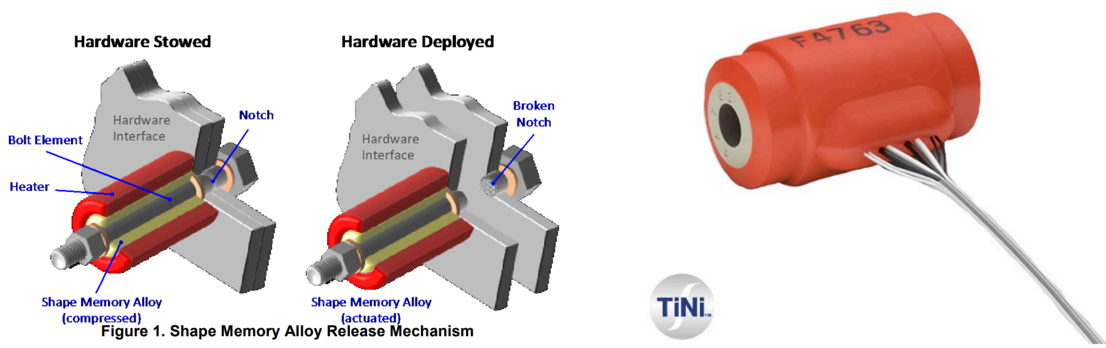

Fig 2. [5,6]

Frangibolts have other applications within space missions wherever an explosive bolt may otherwise be used.

3.2 Deployment

In order to fit the spacecraft within the physical constraints of the launch vehicle's fairing, it is common that parts of the spacecraft need to be deployed once on orbit. Deployable structures are used in many locations on modern spacecraft. I will be focusing on boom type deployable structures as they are commonly used for many different subsystems. Booms are designed to rigidly attach two parts of the spacecraft at a large distance. They are commonly used to create antennas which are longer than would otherwise be possible. They also have applications creating gravity booms, a form of passive attitude control, and moving sensitive equipment such as magnetometers farther away from the spacecraft which will be emitting interference [7]. Booms must be sufficiently ridgid and strong but also collapse into a very small space before deployment. I will be going into four important types of booms, inflatable, articulated, stacer, and lenticular, as these may have applications to my current work.

Inflatable booms are roughly what they sound like. A long sleeve is unrolled and gas is added to erect it [7]. This leaves the booms relatively susceptible to MMOD impacts which make them impractical for most applications. A potential solution is to impregnate the sleeve with resin so that it cures permanently into a tube once exposed to the UV light that the boom will experience once deployed [8]. Fig. 3 is an example of an inflatable boom partially deployed.

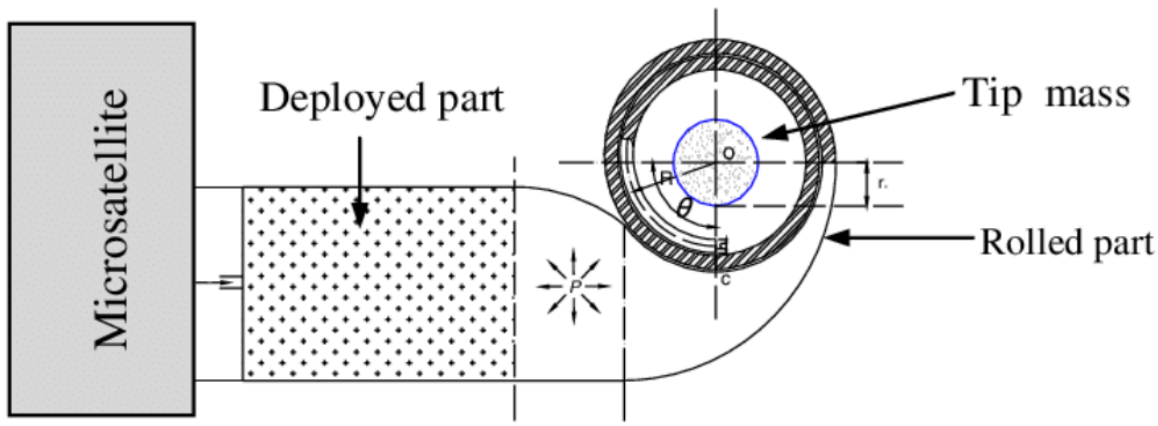

Fig. 3 [9]

It is also possible to reinforce an inflatable boom by laminating the sleeve with aluminum tape to give it added rigidity in certain directions [8].

Stacers are a type of deployable boom which store potential energy in a spring-like structure. While stowed, the structure is compressed and held in place. When deployed the structure is allowed to extend and reach its full length. Stacers have the advantage of simplicity and high rigidity once deployed [7]. Fig. 4 shows an example of a stacer in its deployed state

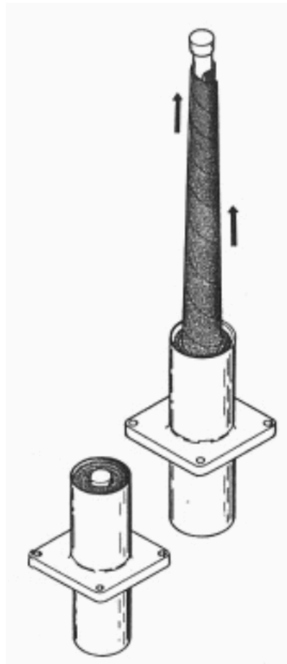

Fig. 4 [7]

Articulated booms are often the first thought that comes to mind when thinking about deployable booms. They consist of many linkages and a tensioning system. When the system is tensioned, the linkages extend creating a rigid structure. While having good flight heritage, they are not favored as much anymore due to their complexity and relatively poor performance compared to stacers for most applications. Fig. 5 shows an example of an articulated boom.

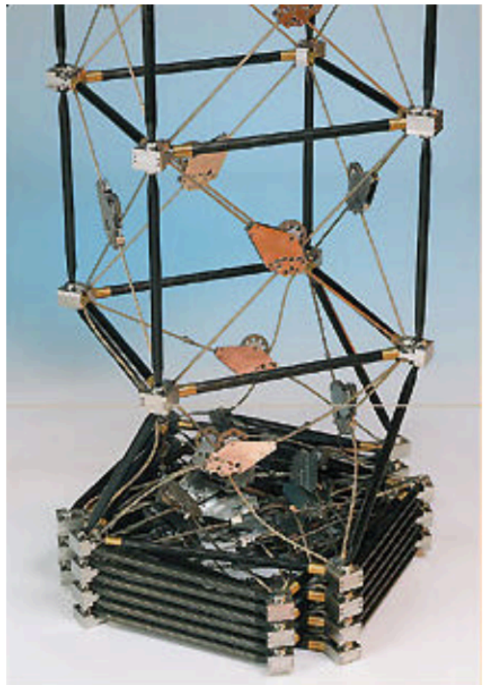

Fig. 5 [7]

Articulated booms do have the advantage of being re-stowable, meaning that they can be collapsed and deployed multiple times. They can also be extended to any given length. This may give desirable flexibility to some designs.

Lenticular booms do not have nearly as much flight heritage but combine many of the advantages of the other booms. They consist of a somewhat flexible material which can still be rolled (Fig. 6). It can be thought of as something like a tape measure in this way. It is deployed in a manner similar to the inflatable boom, but requires no gas to inflate it. This has the added benefit of never being particularly susceptible to MMOD [7].

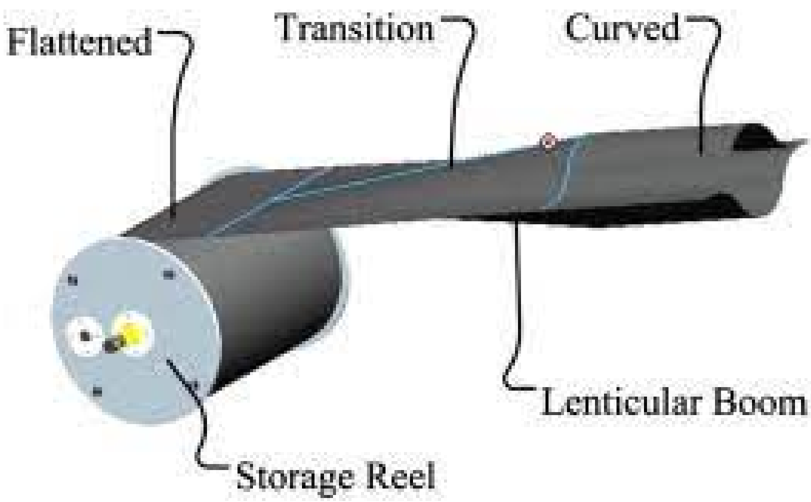

Fig. 6 [10]

While Lenticular booms are highly performant, they lack much of the flight heritage that other deployable booms have.

There are many other types of deployables including sails, dish antenna, and tethers, but many of these designs are riffs off of these mechanisms, and since my work doesn't have a need for such exotic deployables I will truncate the discussion here.

3.3 Pointing

Pointing can be divided into two main categories. Adjusting the pointing of the entire spacecraft and adjusting the pointing of a specific component, also known as gimballing. Gimballing is accomplished by rotating a component about one or multiple axes. I will be discussing only the latter in this paper. Gimbals are sold by many manufactures for many spacecraft applications including antenna pointing, sensor pointing, and most ubiquitously, solar array pointing.

Crucially, electrical circuits will have to be connected from the devices on one side of the gimbal to those on the other side. If the gimbal only moves in a limited range this can be accomplished by a simple flexible cable which is wrapped inside the gimbal and allows the circuit to stay closed during actuation. If the gimbal is to be able to rotate continuously however, slip rings can be used. These consist of a ring shaped contact, which is concentric to the axis of rotation of the gimbal and a sweeper contact which is electrically connected to the ring regardless of the gimbal's position. Northrop Grumman for instance offers a gimbal for solar arrays with up to 120 circuits on separate slip rings [11]. This can give engineers a huge amount of flexibility in their designs.

Gimbals are actuated with a rotary motor. These come in a surprisingly extensive variety. Induction Alternating Current (AC) motors, Brush Direct Current (BDC) motors, Brushless Direct Current (BLDC) motors, and stepper motors [12]. AC motors are largely used for high power applications like pumps and are not of particular interest to me. BDC motors are rather inefficient and have fallen out of use even in terrestrial applications on all but the cheapest devices. BLDC motors and stepper motors however are of great interest to satellites of all sizes due to their versatility and efficient performance. Both of these motors work on a similar principle. The rotor contains permanent magnets and the stator consists of solenoids which are switched electronically. By switching on a solenoid, the magnets in the rotor are aligned with that solenoid. By doing this in series, the rotor is forced to rotate relative to the stator [12].

The distinction between BLDC and stepper motors is in the configuration of the rotors. The rotor has many poles in a stepper motor that each step one small increment each time the solenoids are switched (Fig. 7). A BLDC motor on the other hand has few poles on the rotor and moves much farther each switch (Fig. 8). As a result a stepper motor is slower, more accurate, and has much greater holding torque than a BLDC motor. The figures below show the rotor and stator configurations for both types of motors.

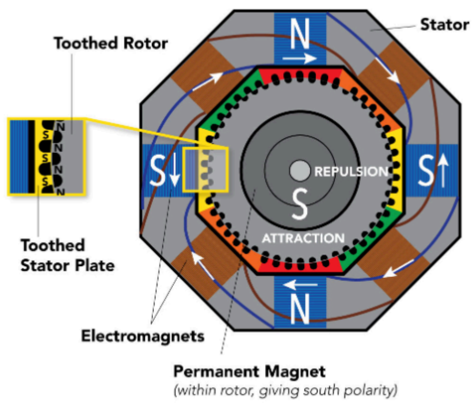

Fig. 7 [13]

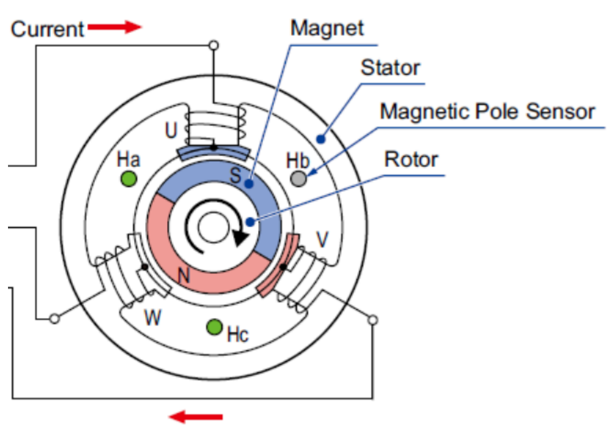

Fig. 8 [14]

If the output torque of the motor is insufficient for the application of the gimbal, gearing can be used to increase the torque. It is common to use a harmonic gear drive to create the gear reduction required for gimbal operation. A harmonic gear drive is a device which can convert fast rotational motion into very slow but high torque rotational motion. The system consists of a stationary spline with a flexible rotating spline engaging it internally. This internal spline is slightly smaller than the outer spline and wouldn't engage with the outer spline, except that there is a wave generator which stretches the inter spline and causes it to engage. By rotating the wave generator, the inner spline progresses very slowly relative to the outer spline. Fig. 9 shows a diagram of a harmonic gear system.

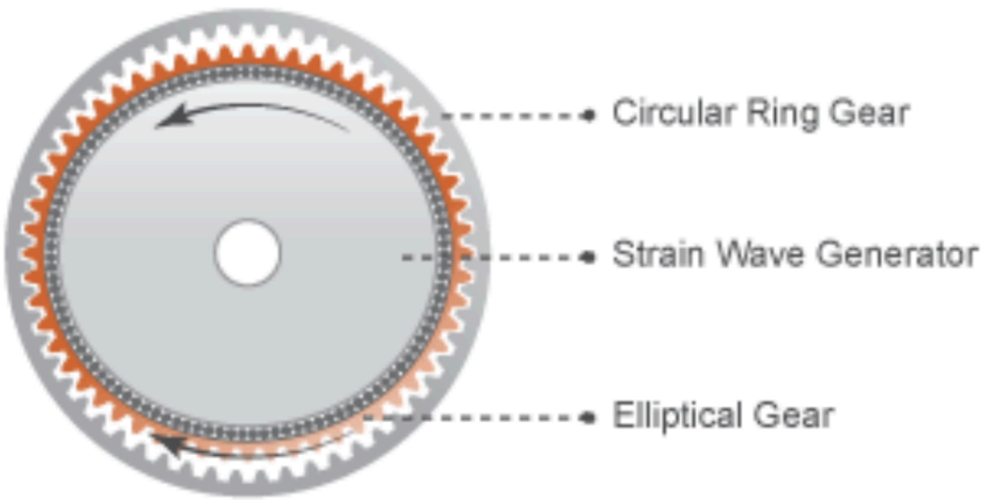

Fig. 9 [16]

These gear boxes are significantly smaller and lighter than their traditional counterparts if high reduction ratios are required, as they are in gimbals.

5.0 Conclusions

Spacecraft mechanisms and actuators are important in overcoming the unique challenges of spacecraft design. By looking at some solutions for release mechanisms, deployable booms, and pointing devices, and the critical roles they play in spacecraft operations, this paper has aimed to demonstrate some of the diversity in design and application of spacecraft mechanisms as well as show the types of problems that have been solved already in the realm of spacecraft mechanisms.

6.0 Sources

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