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Impact of Strain-Actuated Attitude Control Systems for Variant Mission Classes

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Abstract

The University of Illinois, in collaboration with NASA Jet Propulsion Laboratory (JPL) and NASA Ames Research Center, has developed a novel Attitude Control System (ACS) called the Strain Actuated Solar Arrays (SASA), with sub-milli-arcsecond pointing capability. SASA uses strain-producing actuators to deform flexible deployable structures, and the resulting reaction forces rotate the satellite. This momentum transfer strategy is used for jitter reduction and small-angle slew maneuvers. The system is currently at a Technology Readiness Level of 4-5 and has an upcoming demonstration flight on the CAPSat CubeSat mission. An extension to the SASA concept, known as Multifunctional Structures for Attitude Control (MSAC), enables arbitrarily large-angle slew maneuvers in addition to jitter cancellation. MSAC can potentially replace reaction wheels and control moment gyroscopes for attitude control systems, thereby eliminating a key source of jitter noise. Both SASA and MSAC are more reliable because of fewer failure modes and lower failure rates as compared to conventional ACS, while having an overall smaller mass, volume, and power budget. The paper discusses the advantages of using SASA and MSAC for a wide range of spacecraft and variant mission classes.

Keywords: Attitude control system, jitter rejection, sub-milli-arcsecond pointing, fine position control, Vibration dampening, pointing stability

Abbreviations

ACS	Attitude Control System. 2
CMG	Control Moment Gyroscope. 2
mas	milli-arc-second. 2, 4, 9
MSAC	Multifunctional Structures for Attitude Control. 1, 2, 4, 6–9
RWA	Reaction Wheel Assembly. 2, 8
SASA	Strain-Actuated Solar Array. 1–9
SRP	Solar Radiation Pressure. 4

Nomenclature

I_{con}	Moment of Inertia of panel when undergoing contraction. 6
I_{ext}	Moment of Inertia of panel when undergoing extension. 6
I_{panel}	Moment of Inertia of panel. 3
I_{sat}	Moment of Inertia of satellite bus. 3
θ_a	Max deflection angle of the deployable panel in the positive direction. 6
θ_b	Max deflection angle of the deployable panel in the negative direction. 6
θ_{panel}	Deflection angle of the deployable panel. 3
θ_{sat}	Angle rotated by the satellite bus. 3

1. Introduction

Spacecraft attitude control is the process of orienting a satellite toward a particular point in the sky, precisely and accurately. The precision of spacecraft attitude control is critical for many space observatory and optics-based payloads. Satellite pointing precision is quantified using the metrics *pointing accuracy* and *pointing stability* [1].

Pointing Accuracy measures the uncertainty of the pointing of an instrument along a selected direction based on vector measurements to a set of known beacons, such as stars, ground, or space objects. Pointing stability is the duration of time for which the attitude control system maintains pointing accuracy to a defined limit.

Strain-Actuated Solar Array (SASA) Attitude Control System (ACS) is a recently-introduced solution for cancellation of mechanical vibration (jitter), and for producing sub-milli-arc second scale slew maneuvers to provide pointing stability and accuracy. The SASA system utilizes deployable spacecraft panels as multifunctional structures. These panels provide precise, but limited (*mas-scale*), attitude control in addition to their primary functions.

Various science payloads have demanded different levels of pointing accuracy, with optical imaging payloads demanding accuracy up to the nano-radian (milli-arcsecond) scale [2, 3]. Multiple new space telescopes are being designed with unprecedented levels of required pointing accuracy [4, 5, 6], motivating the development of new ACS technologies with enhanced accuracy (while maintaining or improving reliability).

Attitude control for satellites has been achieved using a range of established attitude control actuators, such as reaction thrusters, magnetic torque coils, and momentum management devices [7]. Reaction Wheel Assemblies (RWAs), Control Moment Gyroscopes (CMGs), and nutation dampers are examples of moment management devices. Moment management devices, also known as momentum exchange devices, rotate satellites by temporarily altering the distribution of angular momentum between devices and the rest of the spacecraft. These alterations can then produce a secular change in attitude. Conventional satellites utilize RWAs or CMGs for arbitrarily-large attitude control maneuvers (slews), coupled with vibration isolation systems, to achieve up to *milli-arc-second (mas)*/nano-radian pointing accuracy [3]. Conventional systems for attitude control have been designed without considering the compliant response of the spacecraft. This leads to complex control algorithms that avoid exciting virbational modes of the structures, particularly in deployable panels. Most conventional approaches try to modify the deployable structures to reduce mechanical compliance, which comes at a mass and cost penalty.

Several space science mission lifespans have been shortened due to a malfunction of the ACS, resulting in an inability to provide the pointing required by the science payload [8]. Reliability problems and vibration from high-speed rotating components motivate investigation of new ACS strategies with potential for quieter and more reliable operation.

Current SASA implementations utilize distributed piezoelectric actuators to strain the deployable structures, and the resulting momentum transfer rotates the spacecraft bus [9, 10]. The system has been studied using co-design methods to identify system-optimal distributed structure and control designs [10, 11]. These monolithic actuators have the advantage of inherently improved reliability compared to conventional ACSs since sliding contact is eliminated. A core disadvantage to SASA devices is that they typically have a small strain and slew capability. Initial SASA systems focused on improving pointing accuracy and stability, but must be coupled with other ACS technologies to produce large re-orientations. Also, similar to most momentum exchange devices, SASA cannot provide momentum dumping functionality.

A novel extension of the original SASA system, presented in reference [12], overcomes the small-slew limitation, enabling use of SASA as an independent ACS for some missions. This extension, known as Multifunctional Structures for Attitude Control (MSAC), can produce arbitrarily-large rotations and has the potential to scale to large spacecraft.

This article introduces the capabilities of the SASA architecture and then compares it against well-established ACSs based on several metrics. Then the impact of SASA for a few mission types, across the spectrum of Nano-satellites to Geostationary and deep space spacecraft busses is presented. Finally, the capabilities of the MSAC concept are introduced, and a preliminary comparison is presented.

2. Strain-Actuated Solar Array (SASA)

The SASA system utilizes distributed strain actuators to vibrate deployable panels. The mechanical vibrations cancel the mechanical jitter on the satellite bus, thereby increasing the pointing accuracy and pointing stability of the system. The same deployable panel can be slewed in a direction, and the spacecraft slews in the opposite direction due to the reaction forces. The SASA concept is capable of providing sub-*mas*/sub-nano-radian pointing accuracy and windowed stability. The strain actuators considered for further analysis are bending/extending piezoelectric elements, but a family of other actuators

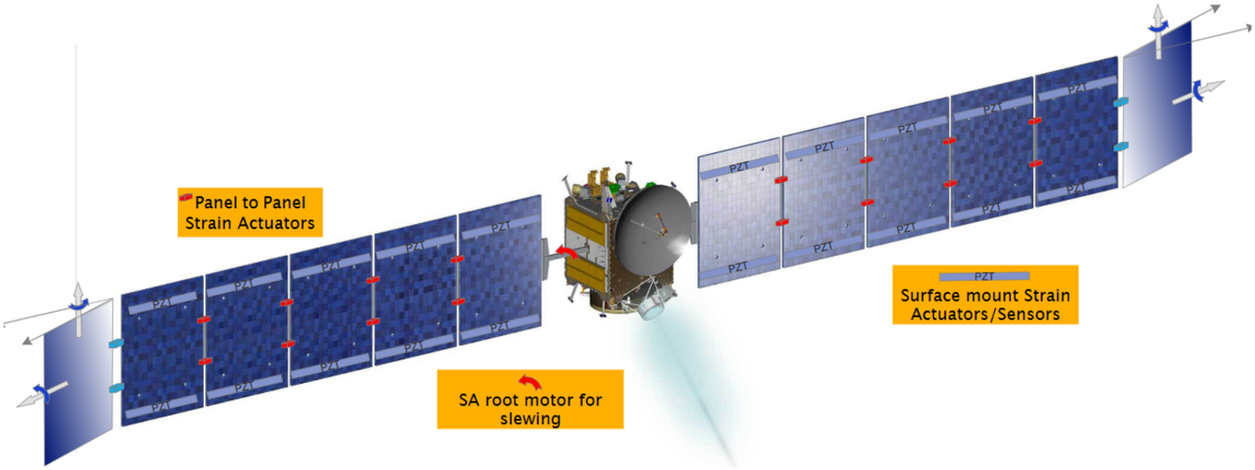

Fig. 1: SASA concept for an SSL-1300 bus[9].

can produce similar results. The resonance modes for the panels can be modified by changing the mass distribution in the solar panel to tailor the performance of the system to the expected noise sources on the bus. A concept of the proposed SASA setup can be seen in Fig. 1.

A simplified version of the SASA system, called the "Cubesat-scale-SASA-demonstrator", capable of providing attitude control about one rotational axis has been developed. The payload has undergone testing in relevant environments, thereby achieving a Technology Readiness Level (TRL) 6. The Pointing payload will fly on a 3U-CubeSat, called CAPSat, as a technology demonstration. CAPSat and the pointing payload hardware can be seen in Fig. 2

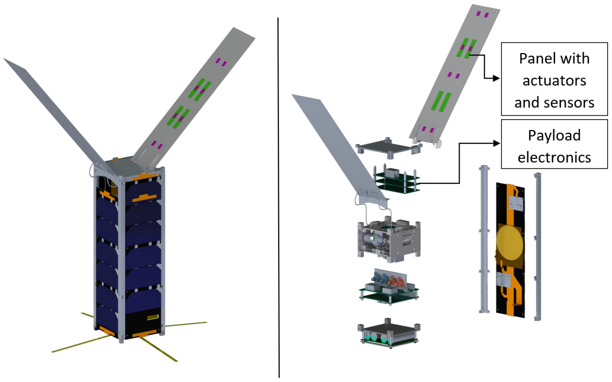

Fig. 2: Render of CAPSat, bus and all 3 payloads integrated (left). Exploded view of CAPSat, showing the Cubesat-scale-SASA-demonstrator (right).

SASA has been developed with an objective to be able to serve a wide range of missions. The technology is scalable, but ensuring a wide bandwidth of operation is challenging for different scales of vehicle structures. This study explores the potential impact of SASA on a variety of missions and satellite buses, ranging from Nanosatellites to communication and deep space satellite buses. The study will explore the potential future impact of the SASA system, as both a primary or a secondary attitude control system, for these buses. Many previously infeasible science payloads can be enabled via the precise pointing capability of SASA. The study also explores the impact of SASA on a wide range and category of science payloads, such as space observatories, gravitational wave interferometry, and Deep Space Optical Communication [2]. All science payloads related to fields listed in the NASA Science Mission Directorate will be evaluated, and the strengths and weaknesses of the SASA system on these objectives will be discussed.

An approximation of the capability of the SASA system to produce a slew of the satellite bus (θ_{sat}) can be seen in Equation (1). This is a key metric that will be used later in the study to compare performance of SASA for different spacecrafts.

$$\theta_{sat} = \frac{I_{panel}}{I_{\text{sat}}}\theta_{panel} \tag{1}$$

Here, θ_{sat} is the maximum slew angle of the satellite, θ_{panel} is the maximum deflection angle of the deployable panel, I_{sat} is the Moment of Inertia of the satellite, and I_{panel} is the Moment of Inertia of the deployable panel.

The oscillating panels produce both reaction torques and forces on the satellite bus. When the panels actuate in an axis-symmetric manner they

Strengths	**Weakness**
• Provides nano-radian pointing capability • Provides fine positioning capability • Multifunctional structure: Eliminates need for vibration isolation systems for payload. • Primary ACS torques produced independent of Solar Radiation Pressure (SRP), thereby maintaining system control authority for deep space missions	• Low TRL • Needs other ACS for large slew maneuvers and counteract secular torque effects (eg. SRP), thereby increasing system complexity.
Opportunities	**Threats**
• Enables a new class of science payload functioning • Enables new and/or improved bus subsystem capabilities	• High TRL conventional ADCS • Electric propulsion system based attitude control

Table 1: Strengths, Weaknesses, Opportunities and Threats of the SASA system as compared to other attitude control technologies.

can produce pure rotations, while operating in anti-axis symmetric manner produces pure translations at small scales. Thus, SASA can be used to dampen rotational and transitional jitter, and slew and move the bus at small scales.

2.1 *SWOT analysis for SASA*

In this section a qualitative discussion of SASA's strengths, weaknesses, opportunities, and threats are presented. A summary of the SWOT can be seen in Table 1.

2.1.1 *Strengths*

The SASA system offers sub-*mas* pointing accuracy to the satellite bus, without the need for complex and heavy vibration isolation systems. Conventional vibration isolation systems isolate a payload from bus vibration, the benefit of a bus-wide system would mean that multiple payloads can have the same pointing accuracy, with guarantees of relative pointing errors between different payloads [13].

Additionally, SASA can also provide fine position control by actuating the deployables in an anti axis symmetric manner. The position control will range from the scale of a few millimeters to a few microns, depending of the deployable mass to satellite mass ratio.

Since SASA relies on the reaction forces from the flexible structures to produce ACS torque, the primary actuation mechanism is independent of solar radiation pressure thus ACS effectiveness is maintained for deep space missions.

2.1.2 *Weaknesses*

The SASA system is a new ACS and currently has no flight heritage. Additionally, to ensure the proper system operation of the system, advanced, high-cadence sensing and processing electronics will be required. Another weakness is that the SASA system cannot provide arbitrarily-large slewing capability as is possible with other ACSs.

To mitigate these weaknesses, the first flight demonstration of the SASA system is on the CAPSat CubeSat mission. The payload has custom-developed high-cadence electronics that have been qualified for flight and space environments. Additionally, MSAC provides arbitrarily-large slewing capability in addition to the base SASA functionalities.

Since SASA is a momentum exchange based device it cannot mitigate the effects from secular external disturbance torque sources such as SRP.

2.1.3 *Opportunities*

The capabilities that SASA offers can enable a new class of satellite missions. The pointing capabilities can enable new space optometry missions, such as space observatories. The position control capabilities also enable drag-free satellite operations with greater efficiency.

The impacts of precise bus-wide attitude control on other bus subsystems can also enable other missions. For instance, precise attitude control allows for high data rate transmissions using optical communications systems, enabling higher cadence science measurements.

2.1.4 *Threats*

The SASA system has competitors from existing high-TRL attitude control systems that have flight heritage. Also, new attitude control strategies that utilize low thrust electric propulsion systems can provide similar pointing stability [14]. Thruster-based ACSs reduces the source of vibrations by eliminating the need for RWAs and CWGs.

The benefits of the SASA system in this case over the conventional ACS is the mass savings, achieved by reduced part count. As compared to Electric propulsion system based Attitude Control systems, SASA can have much faster response times and does not require fuel to remain functional.

2.2 *Impact of SASA on missions*

Several upcoming flagship missions have a need for a precise attitude control requirements for its payloads. Some of the previous, upcoming, and future missions proposed in the upcoming decadal survey are discussed below, and the relevance of the SASA system to the functionality requirements for these missions is described.

Space observatories, such as the Hubble Space Telescope (HST) [3], and surveyors, such as Gaia [13], have high accuracy pointing requirements. Hubble utilized conventional ACS with RWA and vibration dampers. Gaia used no RWAs or CMGs to avoid the main source of on-board vibration; instead, it utilizes cold gas thrusters to achieve high pointing accuracy and stability. Gaia has two separate sensors for the science package with requirements of precise angular separation, something that vibration damping cannot offer without a high mass penalty. Utilization of low thrust cold gas thrusters as an ACS limits the mission lifespan based on the fuel available. Instead, the jitter cancellation capabilities from the SASA system coupled with conventional ACS solutions would serve as viable candidates for the mission, possibly extending the mission lifespan.

Current missions, such as the James Webb Space Telescope [15, 16], WFIRST [17], and LISA [18], utilize a variety of conventional systems and custom tailored fine guiding systems to obtain the desired pointing stability. The SASA system can potentially provide similar pointing requireents but with considerably mas and volume avings, wile having a standardized aand reliable system. SASA can also provide micron-scale position control for drag-free missions [18].

Most current missions have successfully achieved the science objective using coarse ACS coupled with passive vibration isolation, but future missions, such as LUVIOR, Lynx X-ray observatory, HabEx, etc., have more stringent requirements for achieving their science missions. The missions listed above explicitly require active disturbance isolation: *”To keep vibrations from limiting contrast, LUVOIR will also need active disturbance isolation”* [19], and *”The telescope pointing requirement, levied by the instruments, is 2 mas RMS per axis. . . High-precision pointing is key to attaining the required levels of contrast in the HabEx coronagraph”* [20].

SASA is a scalable wide-band active vibration damping system, which would relax the requirement to develop custom-tailored vibration dampers, which are added to conventional ACS ,thereby having excessive mass, volume and system complexity. The SASA system has the potential to reduce mission cost and mass, while being less failure-prone due to the standardization of SASA across several mission types. SASA can simplify the bus architecture significantly for a mission such as the drag-free LISA missions, which will require precise, small-scale attitude and position control.

In addition to conventional mission architectures, new missions can be enabled. SASA is an answer to TA 5.1.4.1 from the 2015 NASA Technology roadmap, and also enables new bus subsystems that can improve capabilities of the satellite. One such subsystem is optical communication systems, such as Deep-space optical communications [2]. Emerging technologies, including manufacturing in space, can have a large impact on the performance capabilities of systems like SASA. For instance, printing solar panels in space can improve the control authority and the bandwidth of operation for SASA-like systems.

Finally, CubeSats can also benefit from SASA due to the fine attitude control possibility, as well as low ACS volume and mass. One example is the field of cluster or swarm-based small satellite missions where formation flight is critical to achieving mission objectives.

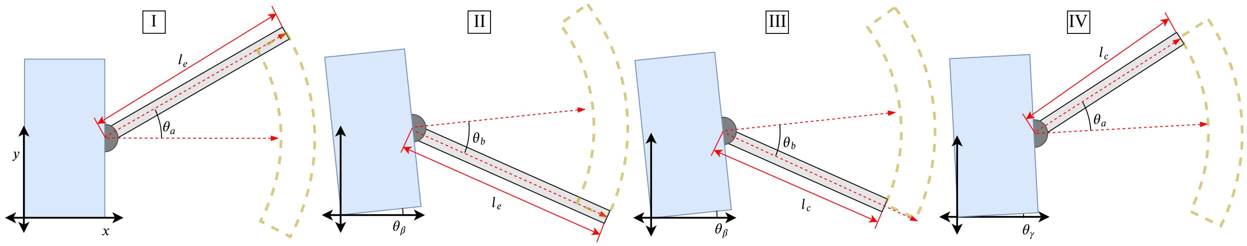

Fig. 3: MSAC system demonstration with the non-holonomic trajectories. The reachable space for the appendage/deployable panel can be seen as the dashed yellow annulus ring sector. Phase V of the trajectory is shown in Fig. 4.

3. Multifunctional Structures for Attitude Control (MSAC)

A novel extension of the original SASA system, called Multifunctional Structures for Attitude Control (MSAC), overcomes the small-slew maneuver limitation, enabling use of SASA as an independent ACS for future missions. MSAC can produce arbitrarily-large rotations and has the potential to scale to large spacecraft. Some older concepts of a similar nature have been demonstrated using geometric control theory [21, 22], but they rely on robotic appendages with sliding contacts to produce attitude maneuvers. The MSAC concept produces similar motions without the use of any sliding contacts, thereby eliminating the need for sliding mechanical contacts (traditional joints), and their associated failure models. MSAC is the subject of US provisional patent filing 62/862,412.

The distinction between the SASA and MSAC systems includes differences in actuator placement and control trajectories that enable secular slewing maneuvers in addition to SASA functionality. The control trajectories that enable the slewing mode can be seen in Fig. 3. This is a non-holonomic trajectory, performing the motion in sequence from Phase I to Phase IV, to produce a small net slew, seen in Fig. 4. These motions of the panel are at millimeter/micron scale (0.1% extension and bending deflection), but can be performed at high frequency. Preliminary analysis of MSAC cycles has shown that with a frequency of ≈1 kHz, a maximum attitude rotation rate of approximately 2 deg/sec can be achieved for the SSL-1300 bus [12].

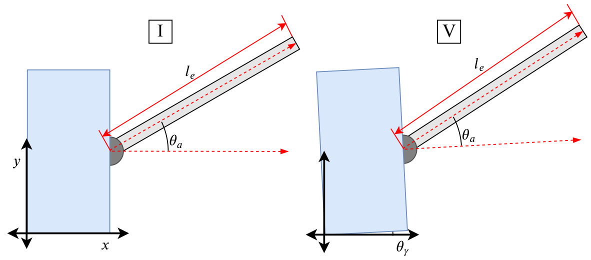

Fig. 4: Illustration of an attitude maneuver using the MSAC system. Phase I is exactly the same as Phase V, except that the satellite has experienced a net rotation of θ_γ

Similar to the SASA system, the performance of the MSAC system can be estimated using a first-order approximations as detailed in Eqn. (2):

$$\theta_{sat} = \theta_\gamma = \frac{(I_{\text{ext}} - I_{\text{con}})}{I_{\text{sat}}}(\theta_a - \theta_b), \qquad (2)$$

where I_{ext} is the Moment of Inertia of the deployable panel when undergoing extension, θ_a and θ_b are the maximum deflection angle of the deployable panel in the positive and negative directions, respectively, and I_{con} is the Moment of Inertia of the deployable panel when undergoing contraction. After a complete cycle, it can be seen that the satellite body has rotated by a small net angle $\theta_{sat}/\theta_\gamma$, while the panels have been reset back to the same relative orientation with respect to the spacecraft as in Phase I (θ_a). The average angular velocity of the attitude maneuver can be approximated using the following linear approximation:

$$\omega_{sat} \approx \frac{\theta_\gamma}{\Delta t} = \frac{(I_{ext} - I_{\text{con}})(\theta_a - \theta_b)}{I_{\text{sat}}\Delta t}, \qquad (3)$$

where Δt is the time required to perform one complete cycle (Phase I through Phase IV), as illustrated in Fig. 3.

3.1 *SWOT analysis for MSAC*

In this section a qualitative discussion of MSAC's strengths, weaknesses, opportunities, and threats are presented. A summary of the SWOT can be seen in Table 2.

Strengths	**Weakness**
• Provides nano-radian pointing capability and fine positioning capability • **Provides large slew maneuvers and achieve slewing rates** • Multifunctional structure: Eliminates need for vibration isolation systems for payload • Can compensate for secular external torque disturbance (e.g. SRP), either temporally or using long term averaging strategies	• Significantly low TRL • Requires momentum management devices to de-saturate, similar to other momentum exchange based ACS, such as RWA and CMG
Opportunities	**Threats**
• Enables a new class of science payload functioning • Enables new and/or improved bus subsystem capabilities	• High TRL conventional ADCS • Electric propulsion system based attitude control

Table 2: Strengths, Weaknesses, Opportunities and Threats of the MSAC system as compared to other attitude control technologies.

3.1.1 *Strengths*

In addiction to the SASA capabilities, MSAC offers arbitrarily large slewing capabilities. MSAC also can achieve slew rate requirements required by modern spacecrafts.

The capability of making arbitrarily large attitude maneuvers and slewing maneuvers enables MSAC to temporarily counteract effects from secular external disturbance torques. MSAC can also rotate the spacecraft to desaturate the momentum gained by the spacecraft unitizing the same external disturbance torque. The correction is performed by reorienting the spacecraft to a pose where the effects of the external torque cancels itself.

3.1.2 *Weaknesses*

The MSAC system is a new ACS and currently has no flight heritage. Additionally, to ensure the proper system operation of the system, advanced, high-cadence sensing and processing electronics will be required.

To mitigate these weaknesses, a Hardware-in-the-Loop test-bed is currently under development to demonstrate performance of the concept, in laboratory conditions.

3.1.3 *Opportunities*

The capabilities of MSAC is similat to that of the SASA system,MSAC can enable similar missions as SASA. The benifits of the MSAC system over the SASA system is that it can be a replacement for RWAs and CMGs, which makes the MSAC ACS having lower power, mass and volume budgets. These savings can allow more power, mass and volume for the payload.

3.1.4 *Threats*

One of the main threats to MSAC is microthruster based ACS, which has high TRL and flight heritage. The benefit of MSAC over a micro thruster based technology is that MSAC does not need fuel for providing ACS. A fuel free fine ACS can potentially increase mission life but also be beneficial to optical payload and power systems which are adversely affected by deposition of fuel on critical components.

3.2 *Impact of MSAC on missions*

MSAC will have a similar impact on missions as the SASA system, due to the similar capabilities. However, MSAC provides the added benefit that it can offload/replace other momentum exchange devices. Since MSAC is a new ACS, most initial mis-

ACS	SASA		MSAC		CMG		RWA	
Bus type	Small	Large	Small	Large	Small	Large	Small	Large
Power (watts)	5–15	50–150	5–15	50–150	8–16	≤ 90	1–30	≤ 90
Mass fraction	0.04	$\leq 10^{-2}$	0.04	$\leq 10^{-2}$	0.3	$\leq 10^{-1}$	0.12	$\leq 10^{-1}$
Volume fraction	0.1	$\leq 10^{-6}$	0.1	$\leq 10^{-5}$	0.7	$\leq 10^{-4}$	0.15	$\leq 10^{-4}$
Failure mode (severity, probability)	1, 1	3, 1	4, 1	4, 1	4, 3	4, 3	4, 2	4, 2

Table 3: Actuator comparison.

sions will use MSAC capabilities in conjunction with ACS(like RWAs and CMG, but eventually, MSAC can be a standalone ACS system capable of providing fine pointing accuracy and stability, along with large slewing capability. MSAC in conjunction with micor-thrusters/magnetic torque coils can have total attitude control authority required be most spacecraft.

In addition to the jitter damping capabilities, MSAC also satisfies the slew rate requirement for several current missions, such as those by Gaia [13]. Future missions, such as the Outer Space Telescope mission concept, require approximately 22 milliarcsecond/sec of slew during science tasks [23], which is within the performance of the example MSAC design [12].

4. SASA and MSAC system analysis for various spacecraft bus types

The SASA and MSAC ACS are compared quantitatively against conventional ACS systems, on the basis of mass, volume and power budget of the system, and severity and probability of system failure modes.

4.1 *ACS comparison*

The metrics utilized to compare the various ACSs and the process for estimating some performance metrics for SASA and MSAC systems for various spacecraft scales are discussed below.

Comparison of the different types of actuators against the proposed SASA system is performed using a variety of metrics. This section introduces the metrics used for the comparison. The performance of ACS for these different metrics is performed assuming all other systems are identical except the ACS used.

- *Power (Watts)*: The power used by the attitude control system to perform maneuvers, considering nominal operation.
- *Mass fraction*: The operational weight of the ACS actuator is used as another metric. This includes the mass of the ACS actuators and associated electronics. The mass fraction is calculated as a ratio of the system to the total spacecraft mass, and hence is unitless.
- *Volume fraction*: The volume required as a fraction of the total volume available in the satellite is used as a metric for performance. This metric is also a ratio of the system volume to the internal spacecraft volume.
- *Modes of failure (severity, probability)*: The predicted models of failure and their severity. This is a qualitative scale and the severity is defined according to the severity scale defined in Ref. [24].

4.2 *ACS types*

Since both SASA and MSAC are momentum exchange devices, they are compared against two other ACS within this class: RWAs and CMG. RWAs and CMGs are the most widely used actuators for spacecraft. The comparison is made for two distinct classes of satellite bus. The “small” bus refers to a standard 3U-CubeSat bus, and is a good representative for most micro-satellite scaled buses. The “large” bus analysis is based on the SSL-1300 bus, which is a standard bus size that has been considered/flown for several GEO telecommunication satellites and a few flagship deep-space missions. Comparison across this spectrum provides an estimate for the scalability of the two systems.

4.3 *Summary*

Table 3 shows a comparison of the metrics across the various ACSs. The numbers for RWAs was based on the Blue Canyon reaction wheel package [25, 26] for the nano-satellite bus, whereas Collins Aerospace reaction wheels were used for estimating the metrics for larger spacecraft buses [27]. Similarly, CMGs were

Spacecraft type	SASA/MSAC benefit	Justification
CubeSats	yes	The small footprint and precise pointing capabilities of SASA and MSAC make it an enabling technology for advanced CubeSat missions with greater science return.
Micro-satellites	yes	The benefits will be similar to that of CubeSats. Science missions which previously were only possible on large satellite buses with conventional ACS are made possible on microsatellites at a lower cost.
Geostationary satellites	no	Most geostationary satellites do not require precise pointing; therefore SASA and MSAC are less relevant for these types of missions.
Deep space satellites	payload/mission dependent	The primary capabilities of SASA and MSAC are independent of SRP effects, are not limited by the fuel carried by the spacecraft, and have fewer failure modes and lower failure rates than conventional ACS. These features make such a system an ideal ACS for deep space missions that require high pointing accuracy and long lifetimes.
Space observatories	yes	A SASA or MSAC system can greatly increase an observatory's pointing capabilities and mission lifetime. Smaller observatories with the same capability are also possible due to the small mass, volume and power footprint of SASA and MSAC.
Space station	no	Current space stations and other human-rated spacecraft do not require precise pointing capabilities.

Table 4: Applicability of SASA and MSAC to satellite scales

estimated using the specifications of the small satellite CMGs available from Honeybee [28], and the values for the larger bus were based on Collins Aerospace CMGs.

The performance metric values for SASA were calculated based on the pointing payload developed for CAPSat, and hence the numbers for SASA for a small bus are close to accurate for a practical system. The numbers for SASA for a larger bus was obtained by scaling the numbers for a small bus using the equations and scaling introduced in Ref. [29] (see Eqn. (1))to obtain similar performance.

The performance metric values for the MSAC system were estimated using the results from the pointing payload analysis, and extrapolated based on Eqns. (2) and (3) and Ref. [12], to achieve similar performance as in Ref. [12].

As seen from Table 3, the SASA system robustness to failure is enhanced by the distributed actuator architecture, and it utilizes minimal mass and volume on the bus. The low mass and volume cost of SASA results from use of deployable panels as multifunctional systems. The improved pointing capabilities for SASA come at a power cost since SASA is not a standalone system, and will need either RWAs or CMGs to provide coarse attitude control of the bus.

MSAC, on the other hand, has a similar mass, power, and volume budget as SASA, but with the benefit of it being a redundant system to conventional CMGs and RWAs. MSAC can also replace the functionalities of these conventional systems, thereby providing power, mass, and volume savings.

Utilizing the results from Table 3, we can now make recommendations for different mission types of using SASA or MSAC based systems. Table 4 summarizes the impact of SASA and MSAC to different mission types. In general SASA and MSAC benefit greatly by the distributed actuation architecture, which greatly increases reliability. Geostationary satellites and human spacecrafts like the ISS, will not benefit from SASA and MSAC based systems and hence have no applicability unless there's a change that demands the higher pointing capability.

5. Conclusion

It can be seen that both SASA and MSAC are promising technologies that can provide sub-mas attitude control capabilities, enabling new missions and reducing the cost for achieving existing missions. One of the greatest hurdles is to prove system reliability and gain flight heritage.

SASA is at a higher TRL, with a flight opportunity to demonstrate operation in relevant environments. MSAC has additional capabilities that make it more desirable than the SASA system. MSAC can be the replacement for conventional momentum exchange based systems, with reduce failure modes and better system performance. MSAC is currently being evaluated using a Hardware-in-the-Loop testbed.

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