VEKTOR-FDA: Concept of a Single Three-Axis Fluid Dynamic Attitude Control System based on Liquid Metal for Small Satellites

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Abstract:

In recent years, the number of satellites in low Earth orbit (LEO) has rapidly increased. In 2020 alone, the number of satellites experienced a significant surge to over 1200 objects, reflecting a threefold annual growth. A crucial factor contributing to this growth is the intensive effort to minimize the size and mass of satellites. Key to this endeavor is a compact, high-density design, coupled with the integration of new innovative technologies. This has led to significant expansion in the field of small satellites.

Advancements in the field of small satellites have been largely driven by universities. Technologies and subsystems of conventional satellites have been successfully miniaturized and adapted to the limited resources of small satellites. As a result, these satellites have been able to handle more sophisticated tasks and explore new application areas. Simultaneously, the demands for attitude control and alignment accuracy have increased, necessitating the use of modern three-axis stabilization systems.

The Fluid Dynamic Actuators (FDA) introduce an alternative approach to attitude control for small satellites, a concept successfully pioneered at the Chair of Space Technology at the Technical University of Berlin. The innovative technology behind these attitude control actuators was developed within the same chair, and the single-axis FDA underwent its inaugural testing during the Techno Sat mission in space. Launched in July 2017, the flight model was implemented and successfully tested in orbit.

A single-axis FDA generally consists of a closed ring-shaped channel filled with fluid, where a pump accelerates the fluid. These actuators are based on the use of a liquid metal alloy to store angular momentum. A bidirectional electromagnetic pump regulates the flow velocity and thus the angular momentum to be stored. A three-axis attitude control system, equipped with three single-axis FDA orthogonality aligned actuators, was launched into orbit and successfully demonstrated its functionality as part of the SALSA mission at the Chair of Space Technology in September 2020.

Achieving attitude control in all three axes traditionally requires the integration of three individual actuators into a system. However, this method lacks mass efficiency. For instance, when rotating around one major axis, the fluid mass of the other two actuators must also be carried along.

The VEKTOR-FDA project investigates an innovative new approach. Liquid metal is encapsulated within a sphere, and through inlet and outlet channels in the sphere, the enclosed liquid metal is set in rotation using electromagnetic pumps. With at least three orthogonally aligned pumps and control over their flow velocity, the liquid inside the sphere can be rotated in any desired direction. Consequently, the angular momentum vector can be aligned in any desired spatial direction. As a result, only a single VEKTOR-FDA actuator is required to control all three a.xes of the spacecraft.

Compared to conventional attitude control actuators like reaction wheels, FDAs provide superior torque with minimal jitter, operate with reduced wear, and eliminate zero-crossing problems. These characteristics, coupled with their compact design, are particularly advantageous for applications that demand compact, precise, and low-vibration attitude control, such as Quantum Key Distribution (QKD), Optical Communication (OpCOM), or Earth Observation (EO).

The VEKTOR-FDA project by the Chair of Space Technology at the Technical University of Berlin was initiated in October 2023 to assess the feasibility of this new technology and evaluate the technical feasibility through the development and manufacturing of a technology demonstrator. The goal is to examine the suitability of this technology by qualifying the demonstrator in a simulated space environment, with the anticipated completion targeted for the end of the year 2025.

This paper provides a comprehensive overview of the motivation, idea, and conceptual framework of the VEKTOR-FDA project. Additionally, it presents the preliminary schematic methodology, the implementation plan, along with initial analysis results and technical concepts.

Key Words: attitude control, small satellites, fluid dynamic actuator, technology demonstration

1 INTRODUCTION

Since the early days of space exploration, scientists have focused on the attitude control of satellites. Precisely aligned satellites are crucial for tasks such as Earth observation and telecommunications.

Recently, there has been a significant increase in the number of satellites orbiting in low Earth orbit (LEO). In 2020, there was a remarkable surge, with over 1200 objects counted, representing a threefold annual increase [1]. This surge is largely due to concerted efforts to reduce the size and mass of satellites. Key to these efforts is the adoption of compact, high-density designs and the integration of advanced technologies, which has led to a notable expansion in the field of small satellites.

The advancements in small satellite technology are largely attributed to the efforts made by universities. By effectively miniaturizing and adapting technologies and subsystems from traditional satellites, small satellites have become capable of performing more complex tasks and exploring new application areas. As a result, there has been a corresponding rise in the need for improved attitude control and alignment precision, leading to the implementation of modern three-axis stabilization systems.

1.1 STATE OF THE ART

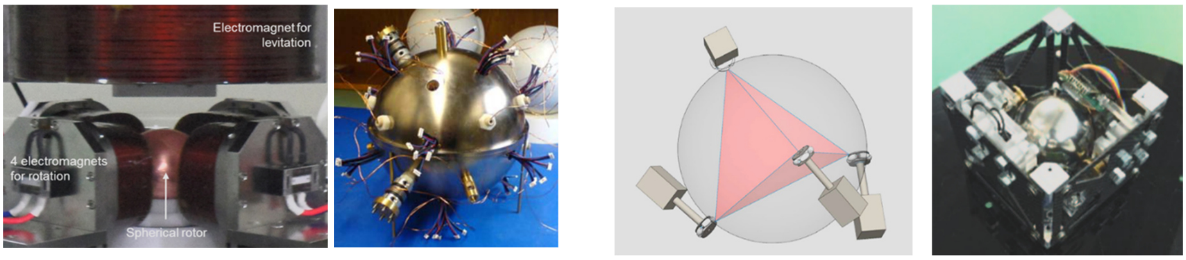
For the execution of spacecraft attitude control, actuators including reaction wheels, control moment gyros (CMGs), or momentum wheels have become standardized instruments, delineating the contemporary landscape of technological progress.

All these actuator function based on a unified mechanical principle. A rigid body, commonly a flywheel, undergoes rotation, thereby producing an angular momentum vector aligned parallel to the axis of rotation. Electric motors are conventionally utilized to convert electrical energy into mechanical energy to drive the rotational motion. The generation of angular momentum is unidirectional, restricting these actuators to the control and manipulation of a singular rotational degree of freedom. This characteristic is commonly denoted as 1-DOF (one Degree of Freedom) actuators. To manage all three rotational degrees of freedom of a body, a minimum of three such actuators is typically necessary, with their rotational axes ideally aligned parallel to the three principal axes of the satellite. Consequently, the implementation of an array of actuators becomes imperative for attaining three-axis stabilization.

The traditional principle of attitude control has faced challenges since the inception of spaceflight. In this process, the torque applied to the satellite is distributed among the actuators and absorbed through the acceleration of the wheel or the gimbal of the CMG, which is associated with cross-couplings between their control loops. The mechanical assembly of the momentum wheel requires precise fabrication and alignment, while lubricants pose challenges in space conditions. Additionally, during transport into orbit, the actuators are subjected to significant mechanical start loads such as vibrations and shocks from launch vehicles. These environmental stressors can induce damage or wear, compromising the smooth operation of the wheels, leading to vibrations, and affecting alignment stability. These drawbacks can be mitigated with high-quality materials and comprehensive verification processes, although specialized solutions like lubrication-free bearings incur higher costs due to the infeasibility of using Commercial Off-The-Shelf (COTS) components. With the progressive demands for miniaturization of attitude control actuators, this traditional principle of utilizing three 1-DOF actuators encounters limitations.

A promising alternative solution to address the challenges at hand was first introduced in the 1960s. Researchers introduced the concept of reaction spheres as multi Degree of Freedom (m-DOF) actuators. In this approach, a spherical body is rotated, and its axis of rotation can be adjusted and manipulated in various directions. This capability allows for the application of conventional control torque by accelerating the sphere and gyroscopic torque by tilting its rotation axis.

In recent years, numerous studies have been conducted in this field, leading to numerous implementation proposals. One such design uses multiple electromagnets to suspend a solid metal sphere between them. Different electromagnets then create rotating magnetic fields which induce eddy currents that ultimately start a rotation in the free-floating sphere about an arbitrary axis. Prototypes of this kind were developed as part of an ESA project in 2009 [2] and the Korea Aerospace Research Institute in 2014 [3]. A different approach to starting rotating and suspension is to use a set of four mechanical rollers arranged around the sphere. Such systems have been tested by the Institute for Systems and Robotics in Lisbon, Portugal [4] and at the Nihon University in Chiba, Japan in 2016 [5].



magnetic induction mechanical rollers

Figure 1. Actuator that utilizes the principle of the reaction sphere and employs either magnetic induction [2] [3] or a mechanical roller [4] [5] drive.

The benefits of reaction sphere technology can address many challenges posed to future attitude control actuators [6]. As an m-DOF actuator, it can counteract cross-coupling issues, and with a free-floating magnetic bearing, it can resolve problems related to adhesion and lubrication. Many developmental prototypes already demonstrate performance comparable to that of reaction wheels. However, researchers still face significant challenges. Miniaturization and complexity are major obstacles. For example, in magnetic bearings, the stator size must be minimized while maintaining a sufficiently strong magnetic field. Additionally, the utilization of a high number of magnetic coils, such as the 20 used in the dipole actuator development branch, adds complexity and increases the risk of failure, particularly in terms of control.

Another approach moves away from using solid-body rotation to generate angular momentum. Researchers are exploring the use of moving high-density fluids for this purpose.

In 2010, research on FDA (Fluidic Attitude Control) technology commenced at the Chair of Space Technology at the Technical University of Berlin as part of a DFG (German Research Foundation) research project. This is a 1-DOF actuator in which liquid metal is enclosed in a ring-shaped channel and set into rotation. The mass flow generates an angular momentum similar to that of a reaction wheel. With the FDA-A2, the ILR was able to create the world's first functional liquid metal actuator [7]. Since then, the technology has been developed step by step until the FDA-A6 has successfully verified the novel technology in orbit on the TechnoSat satellite [8] und [9]. The first single-axis position control maneuvers were carried out on the satellite and the system-specific, relatively large torque was demonstrated. In performance mode, the FDA-A6 is able to deliver a maximum torque of 170mNm with a maximum power consumption of 5 watts.

The extremely low-vibration operation of the FDA compared to reaction wheels could only be partially demonstrated on a vibration test bench, since the sensor noise from the MEMS-acceleration sensors was only slightly better than the vibrations caused by the reaction wheels. The vibrations of the FDA were not measurable. However, better sensors are needed for further investigations.

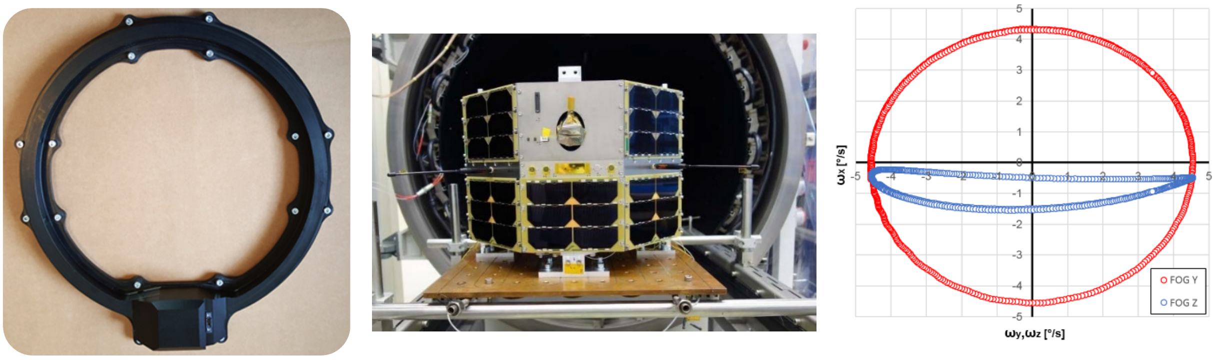


Figure 2. FDA-A6: First space-qualified single-axis FDAs on TechnoSat – 2017 [8] and rotation nutation damping capability.

The suspected nutation-damping properties have not yet been proven on TechnoSat because the FDA-A6 can only act in the z-axis (bluish closed curve). Figure 2, right hand side, shows the closed nutation cone from TechnoSat. Here, the red circle represents the nutational movements in TechnoSat's x- and y-axes. Its almost circular shape also confirms the satellite's geometric symmetry and is shown here in the fact that the smallest and medium moment of inertia are almost the same size. The figure shows the satellite's movements two weeks after the deployment. Here, the absolute rotation rate fell from 8.0 deg/s to 4.6 deg/s and the nutation period increased from 14 min to 37 min within 14 days. Potentially, the FDA could have dampened the nutation via the cross-coupling of the moments of inertia and the relatively small accelerations in the z-axis, although proof would need a second TechnoSat without FDA for comparison under the same conditions.

2 INTRODUCING VEKTOR-FDA: A NOVEL MULTI DEGREE OF FREEDOM ACTUATOR

The VEKTOR-FDA project, led by the Chair of Space Technology at TU Berlin, takes a significant stride forward by delving into the exploration and advancement of a novel m-DOF attitude control actuator. This actuator combines a spherical design with liquid metal FDA technology. Encased within a sphere, the liquid metal is set into motion through a configuration of at least three electromagnetic pumps arranged orthogonally to each other. Through this innovative approach, a single actuator becomes capable of controlling all three axes of the spacecraft.

With this approach, the advantages of both technologies, the reaction sphere and the FDA technology, are combined. The remarkable benefits of utilizing FDA's electromagnetic pump drive, which operates without the need for any moving mechanical components to convey fluid, are harnessed in this context. Potential damages due to mechanical loads such as wear or failure of mechanisms, which can occur due to shock and vibration loads during launch into orbit, are eliminated and thus have no impact on fluid motion [10] and [11]. The moving liquid metals are self-lubricating, and zero-crossing behavior is minimized by an electromagnetic pump drive. This results in low jitter excitation and smoother operation. In direct comparison to conventional attitude control systems such as reaction wheels, this leads to increased directional stability [12]. Additionally, FDAs deliver significantly higher torques compared to a reaction wheel with equivalent angular momentum capacity. Consequently, tasks involving small angle changes can be handled more agilely.

The integration of FDA liquid metal with the advantages of reaction sphere technology enables the spherical shape to facilitate fluid rotation in every axis. This enables the manipulation of the momentum vector in any spatial direction. Consequently, VEKTOR-FDA functions as a m-DOF actuator, effectively managing all three rotational degrees of freedom of the satellite and mitigating cross-coupling effects. Utilizing a minimum of three electromagnetic pumps as fluid drivers reduces both system complexity and control requirements. Furthermore, the simplicity and low demands for precision and stable bearings allow for the adoption of COTS components, promoting cost-effective system implementation. This synergistic approach facilitates the pursuit of a more compact system design and accelerates the advancement of miniaturization efforts.

The VEKTOR-FDA project aims to demonstrate the technical implementation of a demonstrator and assess its suitability for space applications. The initial focus is on developing a spherical demonstrator tailored for small satellites. Insights gained from this phase will inform subsequent efforts to showcase the m-DOF actuator utility for attitude control in 0.5U to 1.5U CubeSats and PocketQubes. Furthermore, the potential scalability of the system for larger satellites is under evaluation.

This paper provides a comprehensive overview of the motivation, idea, and conceptual framework of the VEKTOR-FDA project. As the project is currently in its preliminary stages, this paper focuses on preliminary design concepts that are informed by initial analysis results.

3 PROJECT INVESTIGATION PLANS AND CONCEPT

The VEKTOR-FDA project, initiated in October 2023, seeks to investigate the potential of this innovative technology and assess its technical feasibility through the development and production of a technology demonstrator. The primary goal is to evaluate the suitability of this technology by validating the demonstrator's performance in a simulated space environment, with the anticipated completion targeted for the end of 2025.

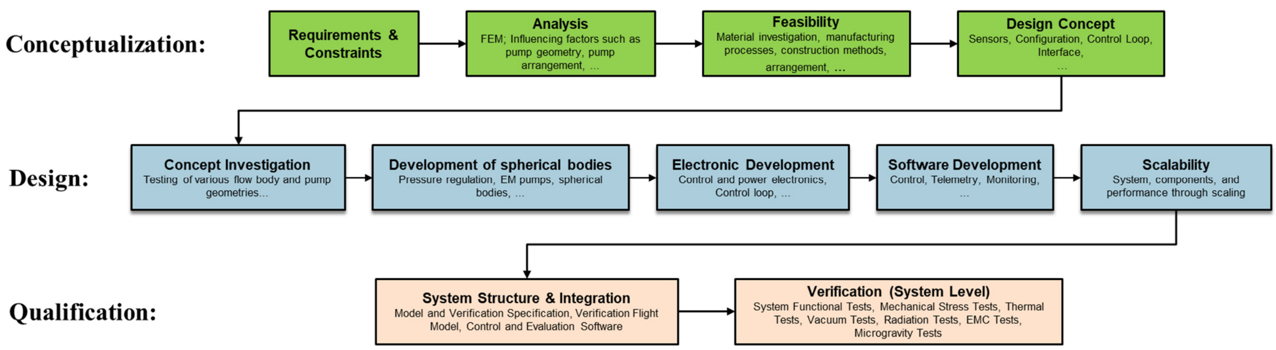


Figure 3. Overview of the project's planned development, delineating initial milestones and key research focuses across three developmental stages.

To accomplish the established objectives, the project is broadly segmented into three developmental phases: Conceptualization, Design, and Qualification. Figure 3 provides an insight into the planned development of the project by outlining preliminary milestones and research focal points divided into the three development phases.

3.1 PROJECT CONCEPTUALIZATION

The project is currently in the conceptualization phase, where the primary focus is on identifying the needs or problems that the introduction of the new technology is intended to address. Clear requirements are derived from this, outlining the challenges to be overcome. Subsequently, various approaches and concepts are examined and analyzed based on the identified challenges. In this phase, focal points have been identified that the project addresses, primarily focusing on analysis, feasibility, and design concepts.

This paper provides a summary insight into the technical aspects and design concepts emerging from this study. It offers an overview of the potentially explored concepts and the methods used to evaluate the initial results. Detailed and further investigations on this topic will be presented in separate subsequent publications.

3.1.1 Analysis and simulation of suitable concept

The first focus of the project is to address the question of whether the idea of rotating liquid within a sphere is feasible at all, and what the technical concept should be to implement it. To address this question, the analysis focuses on investigating various aspects. Flow behavior is explored through analysis and simulation, and the results are evaluated to identify solution concepts.

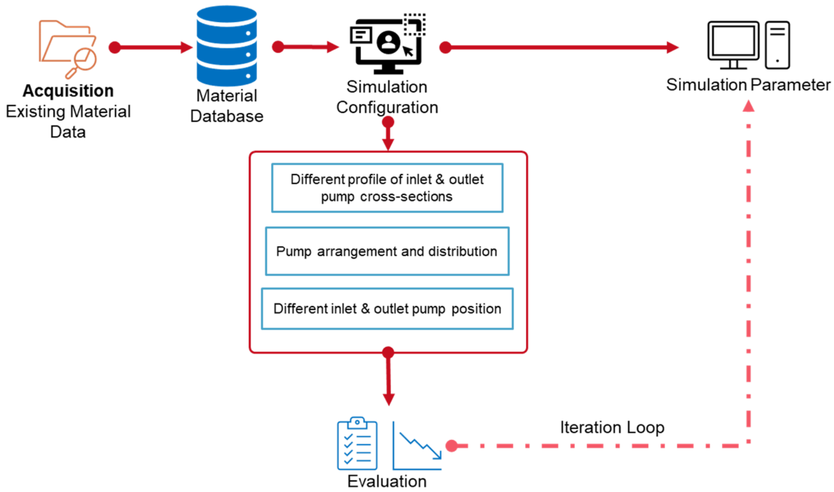


Figure 4. Chain of analysis and simulation to validate the appropriateness of the concept and determine the optimal configuration.

The illustration in Figure 4 depicts the analysis process or cycle considered during the investigation. Initially, all data regarding potential fluids that could be considered were collected. Special attention was paid to fluids with high safety in handling, density, and temperature ranges in which they exist in the liquid phase. In the course of this investigation, liquid metals based on gallium emerged as the fluid with the best properties for the intended purpose.

Based on this, analyses of various concepts such as possible pump inlet/outlet geometry, arrangement, position or material properties were conducted. These analyses were carried out considering variable simulation parameters such as inlet velocities. As a result, different flow profiles can be generated depending on the configuration regarding combinations of pump inlet and outlet geometry, arrangement, and position. The internal flow within the sphere can either spread closer to the sphere's surface or towards the center of rotation axis. Manipulation of the spread is also possible towards the rotation axis. These flow profiles within the sphere constitute the crucial factor determining the resulting angular momentum. The specific configurations that generate particular flow profiles or possess specific characteristics or properties are detailed in the aforementioned publications.

3.1.2 Experimental verification of the analysis and simulation

To confirm the simulation results and identify possible additional aspects not captured by the simulation, simple experiments were also conducted. One of the experiments conducted aimed to determine the performance characteristics of the pumps used to drive the fluid. Figure 5 depicts the setup used in this experiment, which specifically measures the velocity of fluid flowing out of the model sphere and into the pump. This was achieved by optically tracking a tracing particle and measuring the time it takes to flow a certain distance.

The setup consists of a single mechanical circular pump (3) connected via transparent tubes (5) to the model sphere (6). Both tubes are constructed from PVC and have a diameter of approximately 2mm. The tube from the sphere outlet to the pump inlet has a length of 0.69m, which was chosen to ensure that any tracing particles remain visible for a significant number of video frames, making it easier to accurately determine the time spent in that tube. The length of the other tube has not been measured.

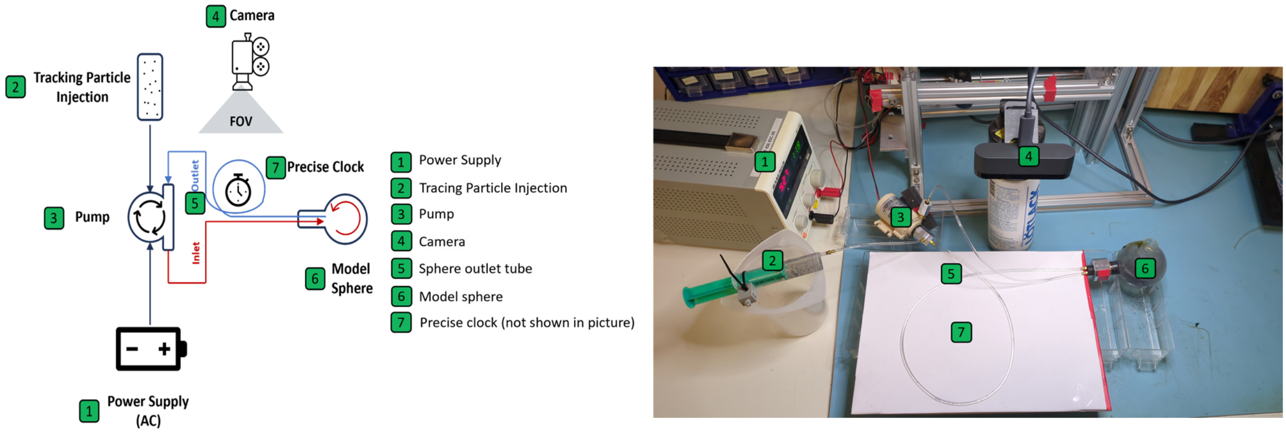


Figure 5. Experimental setup for determination of pump performance characteristics.

The pump is powered by an external variable voltage power supply (1). This experiment used different voltages from 5V to 12V in 1V increments. For this experiment, the fluid being pumped consisted of deionized water with trace particles extracted from a black permanent marker by hand and mixed into the water. Additionally, a clock (7) is positioned beside the tube to measure time, and a camera (4) is installed to view the clock and the sphere outlet tube. The Logitech BRIO webcam has been selected for the camera due to its ability to record at a resolution of 1080p and 60 frames per second. A smartphone clock with a screen refresh rate of 90 frames per second was used for time measurements.

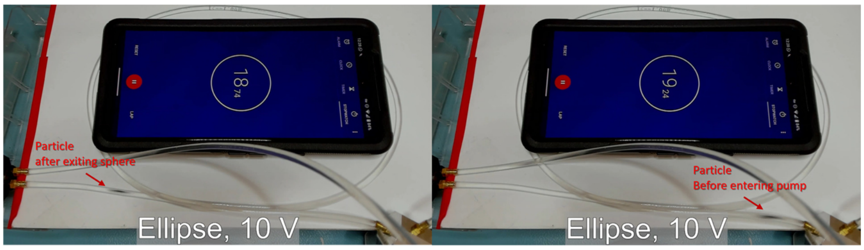
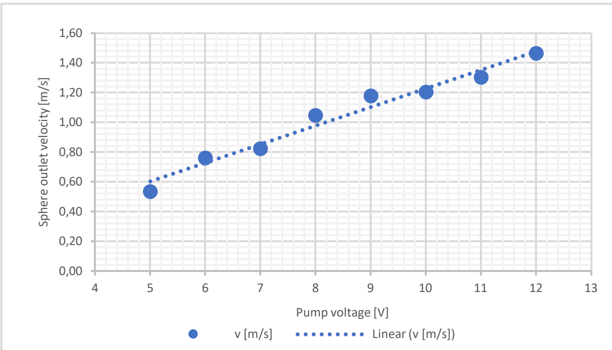


Figure 6 Example of camera perspective recording a large particle.

The experiment captures video of individual particles entering and exiting a transparent tube using a camera. The timestamps of the particle's entry and exit are recorded, and the time spent traversing the tube is calculated by taking the difference. The particle's average velocity can be calculated by dividing the length of the tube by the time it spends inside. Multiple measurements are taken and averaged for each supplied voltage. Figure 6 shows two example frames of a particle entering and exiting the tube.

Figure 7 illustrates a linear correlation between supply voltage and sphere outlet velocity. It is expected that the sphere inlet velocity behaves similarly, although it was not measured. This is based on the continuity equation from fluid dynamics, where for a given stationary system the product of velocity, density and cross-section remains constant. From this, assuming that water is incompressible, it holds that for different tubes with the same cross-section, there must be the same velocity, averaged over the tube's length.



Voltage [V]	**S**phere **O**utlet **V**elocity (**A**verage**)** [m/s]
5	0.54
6	0.76
7	0.82
8	1.05
9	1.18
10	1.20
11	1.30
12	1.46

Figure 7. Averaged measured sphere outlet velocity for a given supply velocity.

Based on the results of the inlet flow velocity, experiments were subsequently conducted to examine the flow profiles inside the sphere with variable channel cross-sections. In summary, the experiments were able to confirm the simulation results. A detailed description of the experimental procedure and analysis of the results will also be addressed in the aforementioned publications.

3.2 INITIAL CONCEPTUAL DESIGN

The design of the VEKTOR-FDA has to meet the Initial constraints and targets performance for application in low earth orbit summary in the Table 1.

One of the objectives is to achieve an operational lifespan of at least 2 years in LEO, corresponding to an accumulated radiation dose of at least 10 krad. Drawing upon the technical expertise gained from past projects involving single-axis or 1-DOF FDA actuator systems conducted at the Chair of Space Technology of the TU Berlin, the VEKTOR-FDA is theoretically estimated to possess a momentum capacity of 100 µNms. This translates to a slew rate of approximately 3.5 °/s for a 1 kg

1U CubeSat, and proportionally higher for smaller satellites. Hence, the desired momentum capacity matches that of the reaction wheels RW1 B, such as those utilized on the first Berlin Picosatellite BEESAT-1 at the Chair of Space Technology of the TU Berlin, albeit with torque 15 times higher [13] and [14].

Table 1. Initial constraints and desired performance metrics for VEKTOR-FDA design

Descriptions	Values
Design mission duration	2 years
Orbit altitude	LEO
Radiation dose	min. 10 krad
Storage temperature	-40°C - 60°C
Operating temperature	-10°C - 50°C
Satellite class	0.5 – 1.5U (scalable)
Angular momentum	100 µNms (target value)
Torque rated	50 µNm (target value)
max. power	2 W
Power standby	<0.1 W

Figure 8 presents the initial conceptual representation of the integrated system, based on the investigation results and primary requirements, highlighting its potential functionality. At its core is the spherical shell (1), which encloses the liquid metal and is equipped with three orthogonally positioned electromagnetic pumps.

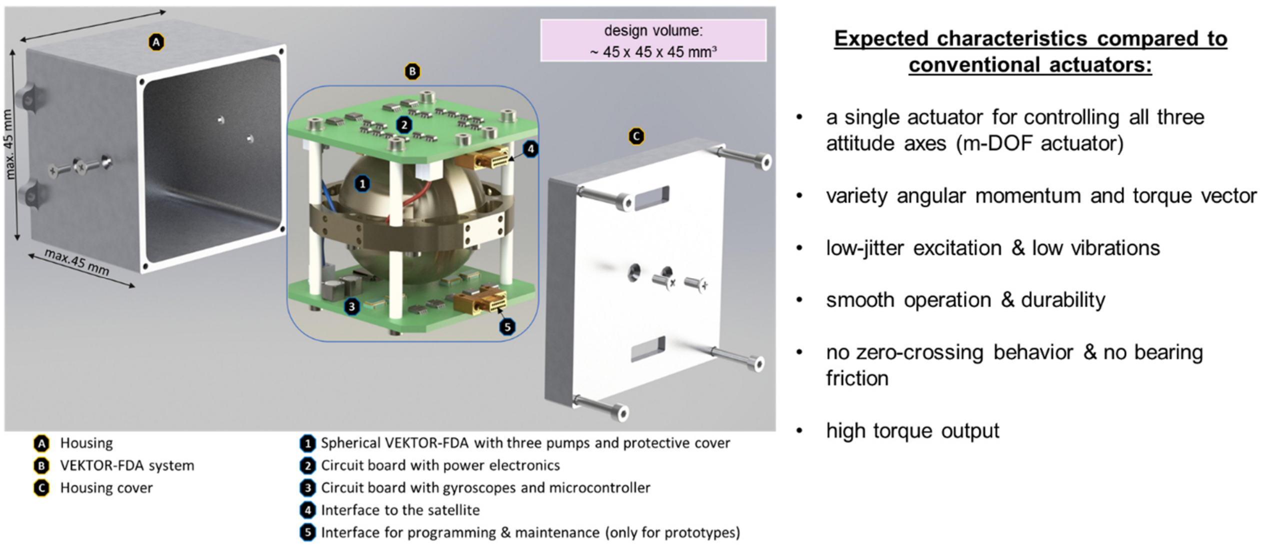


Figure 8. Initial conceptual design and expected characteristics of the VEKTOR-FDA actuator.

Adjacent to the spherical shell, there are two printed circuit boards (PCBs) labeled (2) and (3). The first PCB (2) houses power electronics responsible for supplying energy to operate the electromagnetic pumps. Conversely, the second PCB (3) accommodates microcontrollers, gyroscopes, and interfaces with the satellite. The microcontrollers oversee and regulate the operation of the pumps, including adjusting the required operational currents and logging operational data for telemetry purposes. The entire system (B) is enclosed within a protective, hermetically sealed casing denoted as (A and C). Designed to meet specific constraints and objectives, the casing aims to achieve a compact volume of approximately 45 x 45 x 45 mm³. Consequently, the space requirement for the three-axis m-DOF VEKTOR-FDA actuator amounts to approximately 1/12U. This compact footprint translates to significant space savings, with over 90% of the volume available for accommodating the satellite bus and payload in the case of a 1U picosatellite.

3.2.1 INITIAL TECHNICAL IMPLEMENTATION

The VEKTOR-FDA uses liquid metal for angular momentum storage. The liquid metal is enclosed by a spherical shell. In order to prevent an unlikely bursting of the encapsulation, a secondary cubical structure will be implemented. Additionally, this cubical housing comprises the spherical part, the three electromagnetic pumps, the electronics, and it serves as mechanical interface for the satellite (Figure 8).

Figure 9 depicts a block diagram wherein a 32-bit STM32F413 serves as the main controller. With 320kB SDRAM, the microcontroller offers enough memory to record housekeeping data. This micro controller has been successfully used and tested for 8 quarter unit TU Berlin satellites, namely BEESAT 5-8 and BEESAT 10-13. Traditionally, the ILR relies on redundant communication bus systems, therefore a set of two CAN 2.0 and RS422 controllers will be used as satellite control interfaces. The draft also prepares additional interfaces for future use on other CubeSat platforms, such as I2C and SPI. Two 3-axes MEMS gyroscopes provide angular rates for the fluid momentum controller (FDA-PCU). The gyroscopes serve for the fast relative angle and angular rate control loops. Each electromagnetic pump will be equipped with a sensor for current, voltage and temperature monitoring. The VEKTOR-FDA is not merely designed as a basic attitude control actuator; rather, it is conceptualized as a semi-closed attitude control system. This distinction entails that the system is more than just an isolated actuator; it also incorporates gyroscopes and control loops for relative attitude control. This integrated methodology empowers the system to perform angular velocity and maneuvering at the system level, guided by desired angles. Consequently, this enhances the speed and precision of attitude control operations.

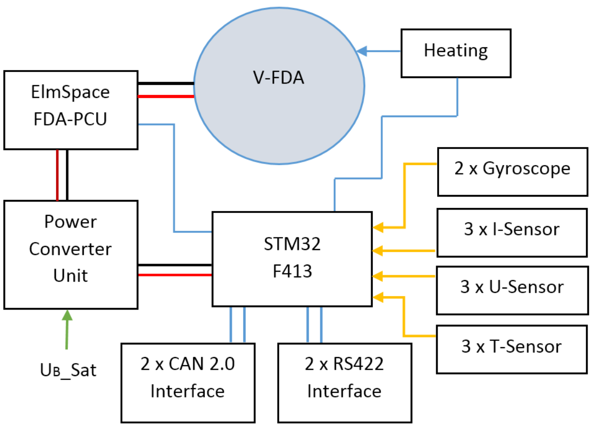


Figure 9. Initial technical implementation of the VEKTOR-FDA system

A heating will be implemented to control the temperature of the working fluid. A Power converter unit fits the unregulated voltage of the satellite to the voltages of the internal electronics. The FDA power controller unit (FDA-PCU) regulates the direction and the pressure of all three electromagnetic pumps individually. Thus, the three forces build up a streaming vector of the rotating fluid, and this leads to a resulting torque and angular momentum.

In order to find a good matching combination of pump and fluid sphere, in a first step, different channel types and electromagnetic pumps will be investigated. Their individual performances will be examined on a small air bearing. The controlling and performance evaluation electronics have been developed already. First calculations and tests indicate a maximum torque of ca. 400 µNm for a sphere of 30 mm in diameter and a power consumption less than 0.5 watts. This torque is 8 times better than the torque requirements.

3.3 QUALIFICATION CONCEPT AND VERIFICATION PLAN

During the qualification phase, extensive tests and verification methods are conducted to assess the technical implementation. This serves to ensure that the specified requirements for operational capability and space operating conditions can be met. Additionally, it verifies whether the defined performance parameters and objectives, such as high-precision stabilization and low-vibration attitude control, can be achieved.

Figure 10 provides a description and an overview of the environmental and functional tests planned to qualify the VEKTOR-FDA system. Two model strands are provided for this purpose: a development model strand and a qualification model strand.

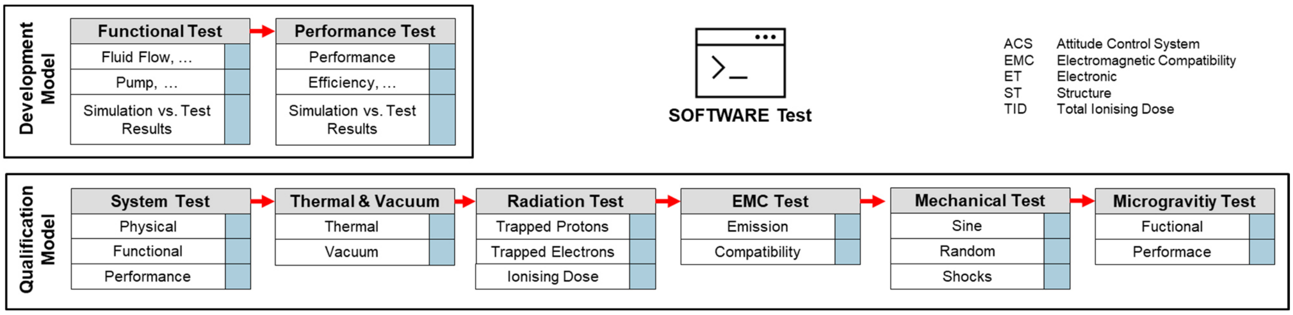


Figure 10. Initial qualification concept and verification plan for VEKTOR-FDA

The development models are utilized or designed during the design phase. They serve to verify the subsystem development, such as that of the control and regulation electronics, and to assess their performance and efficiency. This includes, among other things, examining the suitability of sensor technology and the control and regulation software. The subsystems include the hollow sphere, the pump (electromagnetic/EM pump), the control and power electronics, as well as the control and data acquisition software. The goal is to verify the design at the subsystem level according to the specified requirements.

Once the design has been validated at the subsystem level, the next step involves manufacturing and integrating the complete system (qualification model). The qualification models undergo simulated space environment conditions in laboratory settings. The goal is to meet the requirements for operational capability and the conditions of space operations. This includes tests such as thermal and vacuum tests to assess thermal cyclic loading and the system's integrity. Additionally, the effects of radiation, such as trapped electrons and protons, are examined to determine if aging effects may occur or if the electronics can withstand the intended design lifespan of 2 years. Mechanical tests are also conducted to evaluate functionality after launch into orbit. Functional and performance tests are carried out before and after each of these tests to determine if functionality remains intact or if performance values have changed.

Furthermore, functionality tests, such as those involving air bearings, are planned to assess the performance and functionality of the system. This will help determine whether the system meets the specified requirements for low-vibration operation and expected performance metrics, such as energy consumption or generated momentum. An important test to verify the m-DOF capability of the system. This will be verified by testing this capability using zero-gravity parabolic flights that simulate an environment of microgravity.

4 SUMMARY AND OUTLOOK

The VEKTOR-FDA project is currently in the conceptualization phase. At this stage, initial steps towards technical feasibility have already been taken by conducting simulations and experiments with development models. These measures have confirmed that a rotating flow can be generated inside the sphere through suitable arrangements of inlet and outlet channels as well as pumps. Recent simulations have confirmed that a resultant flow can be generated by the combination of two pumps. These two pumps are arranged orthogonally to each other. Depending on the flow velocity in the respective pumps, the rotation axis between the two pump axes can be inclined. Consequently, the angle of the angular momentum vector between the two axes can be adjusted arbitrarily.

The experimental series are currently being prepared to validate the simulation results and verify the favored configuration of pump inlet/outlet geometry, arrangement, position, or material properties from the previous experimental series. In addition to these experimental series to assess the flow profiles within the sphere, experiments with air bearings are also being prepared. This marks the beginning of the next phase of the project, in which the design of the VEKTOR-FDA will be examined. Initially, the electromagnetic pumps and the design of the hollow sphere will be verified, and initial statements will be made regarding whether the intended goal of generating angular momentum and the required energy intake will be met.

A successful implementation of the VEKTOR-FDA, coupled with the realization of its scientific objectives, could serve as a cornerstone for enhancing space attitude control capabilities in the long run. Over the forthcoming years, the Chair of Space Technology at TU Berlin will delve into rigorous scientific investigations, thereby catalyzing the exploration of new avenues in research.

These include:

- Performing space qualification, testing, and data acquisition for the 3-axis or m-DOF fluid-dynamic attitude control system.
- Investigating the characteristics of the proposed passive nutation damping mechanism through scientific research.
- Assessing the suitability of the technology for laser communication systems and agile, low-vibration, high-precision Earth observation using nanosatellites.
- Conducting broad scientific research to refine, adapt, and validate novel attitude control strategies.
- Exploring the practical applications and potential benefits of emerging manufacturing technologies and materials for spaceflight applications.

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