# AUTONOMOUS DOCKING SYSTEM FOR ASSEMBLY AND RECONFIGURATION IN SPACE FOR SMALL SATELLITES

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## ABSTRACT

As the number of orbiting satellites has rapidly increased in the last few years, the need of space elements that can perform autonomous rendezvous and docking maneuvers with other orbiting elements for different application such as self-assembly and reconfiguration in space are become more pressing. The TAMARIW project is intended to demonstrate such capability for small satellites. This paper describes the project and the modules being developed to realize its objectives at the time of writing. It will also present the technologies and systems intended to be used for performing safe autonomous undocking/docking maneuvers. Additionally, the testing platforms being built in which these proposed technologies and modules are tested and verified will be explained and outlined.

Keywords: Autonomous Docking, Magnetic Docking System, Guidance and Docking Control, Docking Testing Platform, Recovery and Takeover Protocol.

## 1 INTRODUCTION

The development and operation of future space missions will require more space elements (i.e., satellites, modules, robots and spacecraft) that can perform autonomous rendezvous and docking maneuvers with other orbiting elements. Applications such as self-assembly and reconfiguration in space, on-orbit servicing and refueling, debris and retired elements removal are examples of the use of such capability. The TAMARIW "TeilAutonome Montage/Aufbau und Rekonfiguration Im Weltraum" project is intended to develop two identical 3U CubeSats with autonomous docking capability to be launched by the end of 2025. The CubeSats are intended to perform several undocking/docking maneuvers at predefined relative distances. The satellites should be able to find each other, approach each other and dock autonomously using an onboard Guidance and Docking Control subsystem.

In addition, the standardization and partial autonomy of the satellite modules to increase the reliability of the system will be integrated and tested in space where in case of docking control unit failure in one satellite, a Recovery and Takeover Protocol can be initiated. This could reintegrate the functional components of compatible failed satellites and continue to use them. This recycling in space helps to reduce space debris and significantly extend the service life of satellites.

After docking, the satellites should act together, for example their attitude control and orbital maneuvers will be coordinated and executed synchronously as if they were a single unit.

## 2 MAGNETIC DOCKING SYSTEM

Developing an autonomous docking system for small satellite that can guarantee safe automated docking process is very challenging. Small satellites have strict limitations in mass and volume which result in limited power and maneuvering capability. Also, the limited volume restricts the use of complex mechanism for berthing and docking. Magnetic-based docking systems provides a very good solution to overcome these problems since it can help in both capturing and alignment process to perform close range docking maneuvers without the need of using the propulsion system of the satellite which is difficult to use in close proximity.

Normally, the force between two magnetic poles of strength $M_1$ and $M_2$ is proportional to the product of the strength of the magnetic poles and inversely proportional to the square of the distance $d$ between these two magnetic poles as can be seen in Equation (1).

$$F = \frac{\mu_\circ M_1 M_2}{4\pi d^2} \tag{1}$$

Where $\mu_\circ$ is the vacuum magnetic permeability.

The magnetic docking system can be passive or active or a combination of both. The passive magnetic docking system will consist mainly of permeant magnets that can be fixed or movable to control the magnetic field direction and intensity. Whereby an active magnetic docking system will consist of electromagnets that can generate a magnetic field correspond to the passing current which increase the controllability of the system which can result in better and smoother docking process.

One important problem on using such system, is the effect of the disturbance torque that can generate due the interaction of the magnetic field of the docking system with the magnetic field of the Earth as can be seen in Equation (2).

$$\overrightarrow{\tau_d} = \vec{M} \times \vec{B} \tag{2}$$

Where $\tau_d$ is the disturbance torque generated, $M$ is the net magnetic dipole moment of the magnetic docking system and $B$ is the Earth's magnetic field.

Normally the available reactions wheels and magnetic torquers in small satellites are not able to compensate for this disturbance torque. To solve this problem, we need to minimize this disturbance torque by having a nominal zero net dipole moment by using pair magnets per docking port with dipoles with opposite directions. However, and according to Equation (1), this kind of dipoles configuration will decrease the capturing range compered to dipoles with same directions. Also we can conclude from Equation (2) that if the net magnetic dipole moment of the magnetic docking system and Earth's magnetic field are parallel (the angle between them is either 0° or 180°) the cross product of $\vec{M}$ and $\vec{B}$ is a zero vector which eliminated the effect of this disturbance torque.

Other requirement on using such docking systems is that the effect of the generated magnetic field on the internal components of the satellite and especially on the magnetometer should be limited. The induced magnetic field at a certain distance can be calculated using Equation (3).

$$B = \frac{\mu_\circ}{4\pi}\left[3\,\frac{(\vec{m}\cdot\hat{d})\hat{d}-\vec{m}}{|d|^3}\right] \qquad (3)$$

Where $\vec{m}$ is the strength of the magnetic dipole moment and $\hat{d}$ is the distance between the magnet and the effected object. For the magnetometer, this induced magnetic field should be limited to approximately 0.7 $\mu$T.

### 2.1 Passive Magnetic Docking System

Using passive magnetic docking system will eliminate the need to provide additional power which is the case with using active electromagnets. It also increases the magnetic force available for capturing other satellite in the range since a permanent magnet can provide much stronger magnetic field than that of an electromagnet with the same size. In addition, passive magnetic docking system eliminates the need to use an additional latching mechanism to hold the two satellites together.

Since the docking system we need to use should be able to generate an attractive and repulsive forces for conducting several undocking/docking maneuvers, the developed design should be utilizing movable permeant magnets to be able to generate an attractive and repulsive forces. Several designs have been developed and tested to be used in the project.

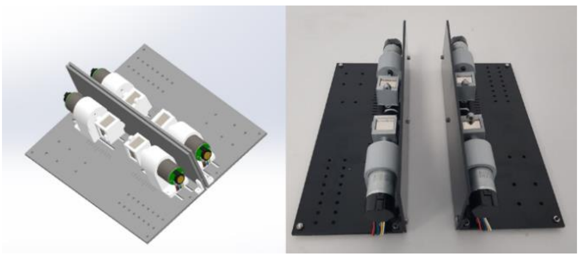

*Figure 1: Passive Magnetic Docking System I*

The first design shown in Figure (1) is using two N45 NdFeB rectangular permanent magnets with dimension of 20x20x20 mm and remanence of 1.33 T to 1.37 T directly attached to two motor shafts on each docking side. The testing result shows poor performance of the motors due to the interference of the strong magnetic field of the permanent magnet as they are directly attached to the motor shafts. This results in poor magnetic field controllability.

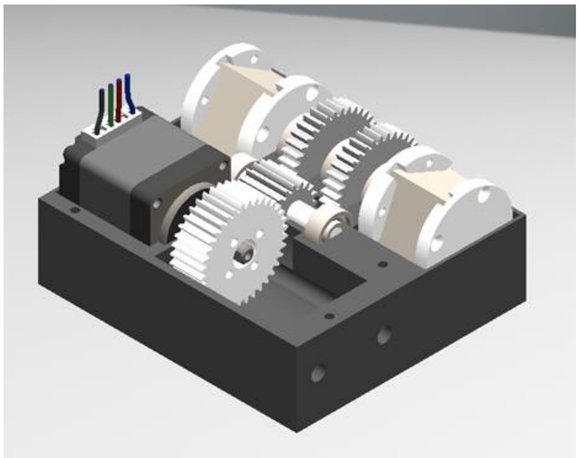

*Figure 2: Passive Magnetic Docking System II*

In second design shown in Figure (2), a gearbox is designed to use only one motor to rotate two magnets in the opposite directions. The whole gearbox was required to be contained in the size of 80x80x80 mm. The motor used in this design is a stepper motor which can provide better performance than that of a geared DC motor. The design of a gearbox came with a size limitation which rise many manufacturing difficulties to overcome. This increases the complexity of the system and thus increases the risk of failure.

Controlling the magnetic field for smooth docking process using passive magnetic docking system has proven to be a very difficult task. Also, the reality that the magnetic force generated form the magnetic port is always active create high risk of attracting unwanted ferromagnetic objects that can cause damage to the satellite. In addition, the high effect of the generated magnetic field on the internal components of the satellite makes the using of such system not applicable to the project.

### 2.2 Active Magnetic Docking System

In this system, one satellite side of 100x300 mm will be defined as the docking side. The active magnetic docking system will consist mainly of four electromagnets with ferromagnetic cores that are placed at the corners of the docking side. This will help in the alignment of the satellites as the force exerted on the satellite corners due to the magnetic field will be controllable via Pulse Width Modulation (PWM) signals. Each electromagnet will be H-bridge driven and controlled through PWM and direction signals to have dual polarity electromagnet with controlled magnetic field strength.

Each electromagnet will have approximately 520 turns with a rated current of maximum 2.5 Ampere at 5 volts with a diameter of 35 mm and a length of 50 mm and about 250 grams of weight.

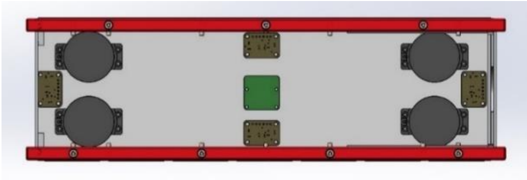

*Figure 3: Active Magnetic Docking System*

A ferromagnetic core of 16 mm diameter from Invar 36 (nickel-iron alloy) which displays high dimensional stability over a range of temperatures is being used. Maximum magnetic field can be generated at rated current at the surface of the core is approximately 70 mT. A magnetic force of approximately 0.01 Newton at 100 mm distance between two electromagnets can be measured at rated current. A very simple latching mechanism will be used to keep the satellites latched. A small Neodymium permanent magnet will be placed on the internal end of the electromagnet core. It will be used to hold the satellites together when the electromagnets are turned off and to increase the magnetic field strength when an attraction force needs to be generated.

The neodymium permanent magnets should be placed so that the total magnetic moment of each pair is minimized, and the magnetic field generated from them will have limited interference with other components inside the satellite.

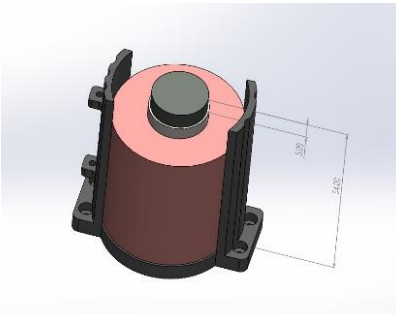

*Figure 4: Electromagnet with Latching Mechanism*

Two polarities configurations can be activated depended on the needed conditions for the rendezvous and docking operation, Identical Polarities configuration or Alternating Polarities configuration.

The Identical Polarities configuration is attained by turning the electromagnets in each satellite with the same polarity as shown in Figure (5).

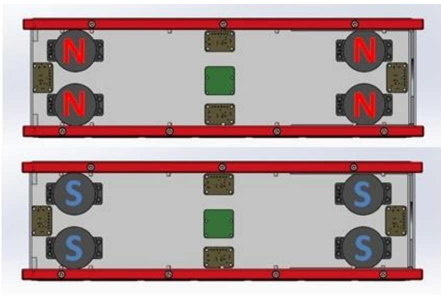


*Figure 5: Identical Polarities Configuration*

Alternatively, the Alternating Polarities configuration is attained by turning the electromagnets in one satellite in alternate form as shown in Figure (6). This will ensure that the disturbance torque from the geomagnetic field is minimized. However, the capturing force between the satellites will be smaller than the case where the electromagnets are polarized the same way. In addition, the alternating polarities configuration will help in the Alignment process as it will reduce the probability of misalignment compering to identical polarities configuration.

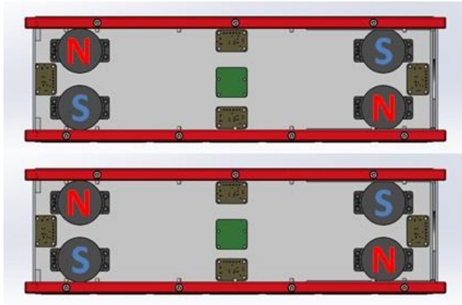


*Figure 6: Alternating Polarities Configuration*

To be able to perform several undocking/docking maneuvers, a dedicated power distribution unit with its own battery pack will be used for the magnetic docking system.

## 3 GUIDANCE AND DOCKING CONTROL SUBSYSTEM

To perform safe autonomous undocking/docking maneuvers and to minimize the risk of failure or operational error, a multistage guidance sensor subsystem has been utilized. In this system, the docking side of each satellite will have three stages of sensor systems as shown in Figure (7).

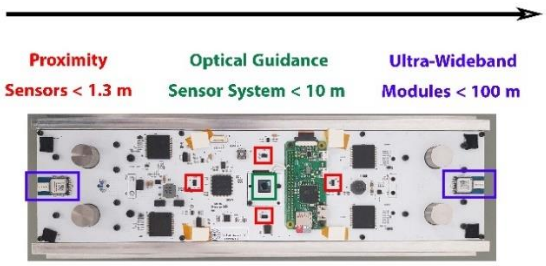


*Figure 7: Guidance and Docking Control Subsystem*

The first stage will be using two Ultra-Wideband (UWB) modules to estimate the relative distance and orientation of the other satellite for a medium relative distance range less than 100 m. Meanwhile, the second stage will be using an Optical Guidance Sensor System consist of a camera with 8 LEDs indicators to identify the docking surface and the relative distance and orientation of the other satellite for a short to medium relative distance range less than 10 m. Finally, and for the last stage, four Time-of-Flight proximity sensors that can measure ranges up to 1300 mm in 1 mm resolution are used to indicate the relative distance, velocity, and tilt angles of the other satellite for a very short distance range less than 1300 mm and up to proximity range of 1 mm.

An Optical Guidance Sensor System that can estimate the relative position and orientation of the other satellite and robust against external light sources is needed. The developed algorithm uses a camera to take images at a given interval of a target satellite with LED markers placed in patterns on each surface. These images are pre-processed to remove most external light sources and then all bright light sources are tracked. Each LED on the target satellite blinks a specific binary code that allows the system to distinguish the LEDs on the target satellite from any other light source and determine the LED's corresponding model points on the target satellite model. The sensor then estimates the relative position and orientation of the target satellite using Perspective-n-Point (PnP) algorithm.

The Docking Control Subsystem is consisting of an STM32F4 ARM Cortex M4-based high-performance 32-bit microcontroller and a Raspberry Pi Zero 2W ARM Cortex A53-based 64-bit single-board computer clocked at 1GHz.

The electromagnets are only activated for Capture and Alignment if other docking surface are in the range of a threshold distance (ca. 30 cm) and both docking sides are aligned with each other in a face-to-face manner with a predefined clearance value of +/- 30° in roll/pitch/yaw. Two modes of operations are implemented for the developed ports where the electromagnets are set to generate an Attraction/Repulsive force for the corresponding Docking/Undocking operation.

The docking controller will require real-time computing with minimum overhead and fault tolerant capabilities. Therefore, the Real-time Onboard Dependable Operating System (RODOS) will be utilized. Most development failures come down to the complexity of the system. RODOS is designed for applications demanding high dependability with simplicity as its main strategy. The Operating System was designed using object-oriented C++ interfaces with real-time priority-controlled primitives multithreading and time management. Its' microkernel provides support for resource management, thread-safe communication and synchronization, input/output, and interrupts management. In addition, it is fully pre-emptive and uses priority-based scheduling and round robin for same priority threads [3]. It has Middleware with Topics and Subscribers beside a Gateway that brings Topics to other RODOS nodes may exist in the system.

RODOS will be running on the STM32F4 microcontroller and will be provide the software framework for running the docking controller and gathering sensors information from stage one and stage three of the guidance sensor subsystem. Whereby stage two will be running on the available Raspberry Pi Zero 2W. Every Satellite will scan its surrounding for targets and possible obstacles using the onboard Optical Guidance Sensor System and at the same time receive Satellite Status Reports from nearby satellite using the Wifi modules available on the Raspberry Pi single board computers. The Satellite Status Report will contain information about the Satellite position, attitude, and fuel & power remaining capacity.

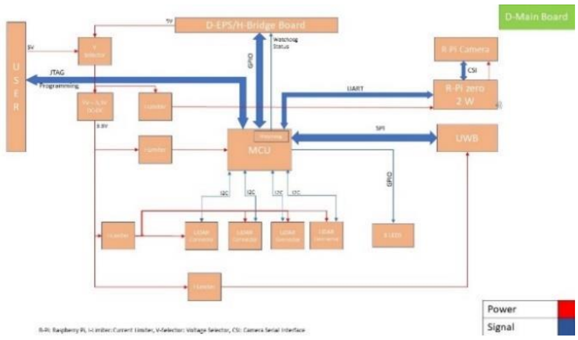


*Figure 8: The Block Diagram of the Guidance and Docking Control Subsystem*

The Guidance and Docking Control (GDC) subsystem is set to operate in autonomous mode where only main mission commands and sensors information will be exchange between the GDC and the satellite's main On-Board Computer (OBC) to coordinate between the Attitude Determination and Control System (ADCS) of the satellite and the GDC subsystem during the rendezvous and docking operation.

## 4 DOCKING TESTING PLATFORM

Testing and validating autonomous space systems require testbeds for on the ground experimental validation of autonomous proximity navigation and docking maneuvers of CubeSats in a frictionless space-like environment. The Chair of Aerospace Information Technology at the University of Würzburg has developed a Space Maneuvering and Docking Facility to help researchers and students understand and get familiar with basic spacecraft and satellite subsystems and to develop and test different control algorithms and strategies for space rendezvous, docking, and formation flying in a frictionless space-like environment [1].

*Figure 9: Space Maneuvering and Docking Facility at the University of Würzburg*

To simulate such environment, air bearing vehicles able to navigate in an almost frictionless environment with three Degrees of Freedom (3Dof) consisting of two components of translation and one angle of rotation are developed. The vehicle consists mainly of a mechanical structure with pressure release nozzles as steering thruster actuators. In addition, one reaction wheel to control the orientation of the vehicle is mounted at the center of the vehicle. To support the structure, flat circular air bearing pads which produce frictionless motion on a flat and smooth surface of glass plates for microgravity environment are used. The propulsion air supply subsystem of the floating vehicle consists mainly of compressed high-pressure air tanks, inline pressure reducers, proportional valves, and pressure sensors to control the flow rate to the air.

One of the difficulties with testing such system is the limitation of the air supply inside the mounted high-pressure air tanks. Filling these tanks take time and making the testing process uncomfortable as it must be interrupted very often. Therefore, several testing platforms have been developed for testing the docking system in different stages of development.

### 4.1 Testing Platform for Measuring the Magnetic Force and Alignment Capability

The Platform has been developed with a mechanism to lift and control the hight of one of the docked satellites while the other satellite is put on a very precise scale to measure the exerting force by the magnetic field. The mechanism is designed to provide as much as freedom possible to observe the alignment capability of the magnetic docking system horizontally.

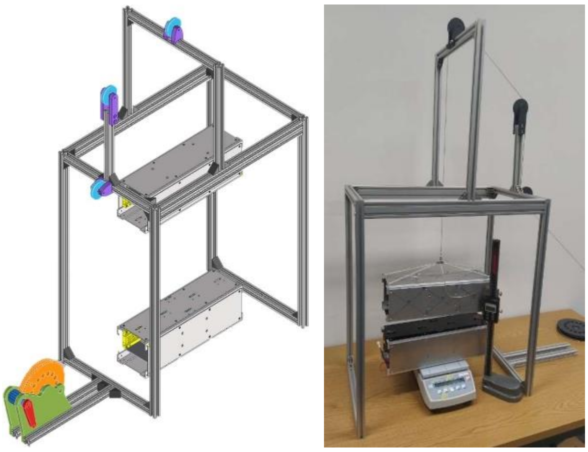

*Figure 10: Testing Platform for Measuring the Magnetic Force and Alignment Capability*

In this platform, the forces between the magnetic docking ports are measured at different distances. In addition, the magnetic dipole generated from the magnetic docking system are measured at different positions. Also, the alignment of the two satellites is tested horizontally with different polarities configurations.

### 4.2 Testing Platform for Measuring the Alignment Capability and Testing the Docking Controller

The Platform has been developed with a mechanism to lift two satellites and keep them apart at different relative distances and orientations. The mechanism is designed to provide as much as freedom of movement as possible to observe the alignment capability of the magnetic docking system vertically.

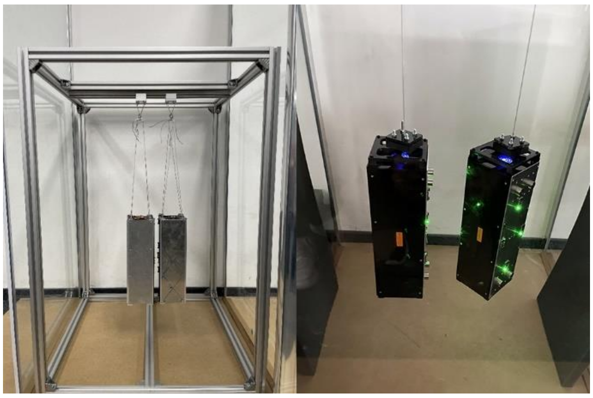

*Figure 11: Testing Platform for Alignment Capability and Testing the Docking Controller*

In this platform, the magnetic dipole generated from the magnetic docking system are measured at different positions. Also, the alignment of the two satellites is tested vertically with different polarities configurations. In addition, the controller to control the magnetic force for a smooth docking process will be tested and verified. In this controller, feedback from the proximity sensors and the optical guidance sensor system to indicate the relative distance and velocity of the other satellite will be used.

### 4.3 Testing Platform in 3Dof Frictionless Environment

In this Platform, the floating vehicles used in the Space Maneuvering and Docking Facility are redesigned to accompany the CubeSats to test the capture and alignment capability of the magnetic docking system in 3Dof almost frictionless environment.

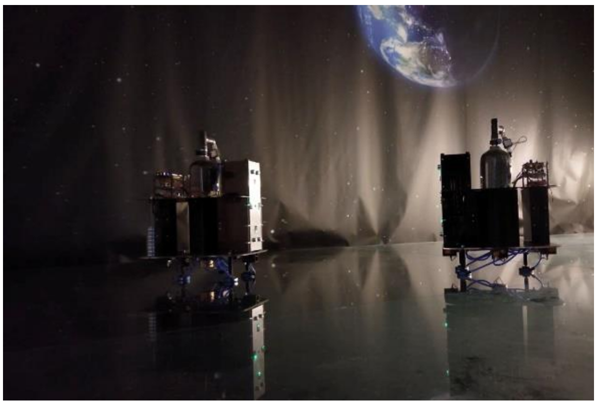

*Figure 12: Testing Platform in 3Dof almost Frictionless Environment*

In this platform, the alignment of the two satellites is tested in 3Dof almost frictionless environment with different polarities configurations. In addition, the controller to control the magnetic force for an autonomous docking process will be tested and verified. In this controller, feedback from the multistage guidance sensor subsystem will be used to indicate the relative distance and velocity of the other satellite.

## 5 RECOVERY AND TAKEOVER PROTOCOL

In order to increase the reliability of the system and to demonstrate the standardization and partial autonomy of the satellite modules and in case of docking control unit failure in one satellite, a Recovery and Takeover Protocol can be initiated. In this protocol, an external docking control unit of another nearby satellite can send commands to the actuators and receive sensors information directly from the recovered satellite over wireless connection.

Once failure is detected, the docking control unit will start searching for other nearby satellite's docking control unit by sending a Recovery Request message. The message will include the control unit ID and the time in which the failure has been detected. If one nearby satellite receives the message and it has free resources to takeover, it should send back an Acknowledgement and Takeover message that include the responder docking control unit ID. As a result, a connection will be established between the new docking control unit and the actuators and the sensors in the recovered satellite.

Moreover, the protocol can also be initiated without a failure being identified. In this scenario, the satellite want to takeover will send a Takeover message directly to the other satellite. The recovered satellite should respond with an Acknowledgement message to establish the connection.

To demonstrate the effectiveness of this protocol, an undocking/docking maneuver will be performed using the protocol.

## 6 CONCLUSION

This paper has presented the docking modules being developed for CubeSat to perform several autonomous undocking/docking maneuvers. The guidance and docking control subsystem consist of multistage guidance sensor systems for safe docking process was described. The newly developed docking testing platforms being used to demonstrate and verify the developed modules and systems were explained. In addition, a new proposed recovery and takeover protocol to increase system reliability and robustness was presented. Further publications will be made to cover in depth the mentioned topics in this paper and show the obtained results from the developed technologies.


## Acknowledgement

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