# Autonomous assembly and reconfiguration in space
# TAMARIW

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## 1. Introduction

The vision is a (physical) structure that cannot be put into orbit all at once and therefore builds itself from autonomous individual elements. We allow the intervention of operators to enable and demonstrate teleoperated assembly, e.g. in case of failure or very complex actions. The demonstration of the core technologies required for the semi-autonomous assembly of structures, e.g. the self-organization of the structural elements, form the basis for a number of important strategic goals, such as the Space Factory 4.0 (funding measure goal: advanced strategic capabilities). The capabilities to be demonstrated will also be needed in the assembly of heavy loads as well as large light loads that exceed the capacity of a single launcher. Another application would be structures consisting of both expensive/safety critical and low cost components. For example, propellant for a very large spacecraft could be carried by cheaper, less reliable launchers. More valuable payloads and electronics could be brought with reliable but expensive launchers, and humans or even plutonium batteries could be transported with the most reliable and therefore most expensive launchers. For example, the mirror segments of a mega-telescope could be brought into orbit separately and assembled there. Large solar cell arrays in space could also be successively built up and expanded over a longer period of time.   Furthermore, the standardization and partial autonomy of the satellite modules based on the Yete-I/Yete-II technologies [QUELLE] further developed within this project could allow the functional components of compatible failed satellites to be reintegrated and reused. This "recycling" in space helps to reduce space debris and significantly extend the service life of satellites.

## 2. *The Mission*

In TAMARIW, we will demonstrate a first step for this vision, the in-orbit assembly of functional modules. Two 3U CubeSats shall perform autonomous docking as shown in Figure 1.

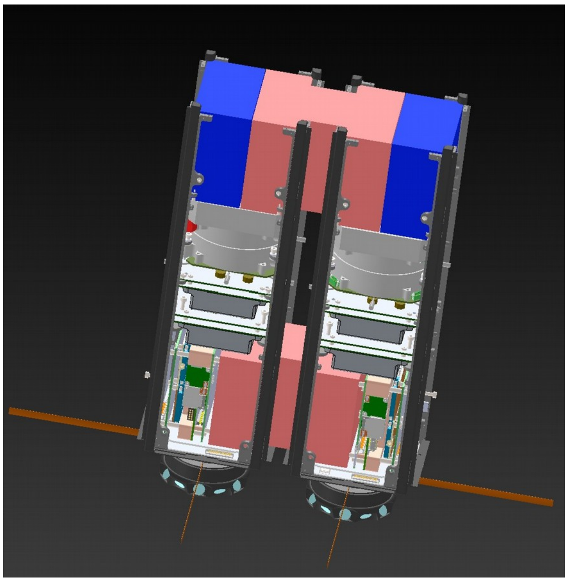

*Figure 1: Both satellites docked together.*

Here, two 3U CubeSats in the same orbit represent the autonomous functional submodules: They will autonomously find each other, approach each other and dock with the docking port attached to them. After docking, they will act together, so that, for example, their attitude control and orbital manoeuvres will be coordinated and executed synchronously, as if they were a single satellite. The next step (not included in TAMARIW) would be to put several larger components into the same orbit, they will approach autonomously and dock one by one to build up the larger target structure, reconfigure it and even replace modules.

Our scientific goals are very demanding and unique even for large satellite projects. Autonomous docking has so far only been known from multi-million euro projects where modules dock with the ISS, for example. This also happens under the supervision of many operators worldwide.

Our two 3U CubeSats will start already docked in the launcher. After stabilization and LEOP phase, we will start with simple docking manoeuvres. First they separate and wait until they drift only a few centimetres apart. Then we will try out the first autonomous (re)docking, which is teleoperatively supported in case of failure. After that, we will test the docking procedures with a larger distance of about one meter and then progressively increase the distances as long as the fuel lasts.

## *3. Docking Phases*

We will divide the docking manoeuvres into the following phases:
1. *Orbit Manoeuvre* (300 m ... kilometre distance) Using 1D powerful main thruster
2. *Long-Range Approach* (100m ... 300m) Using 1D powerful main thruster
3. *Close Approach*(1 ... 100 m) Using 3D thrusters located in all 3 axes of the satellite
4. *Final Approach* (< 1 m) Using magnetic forces
5. *Docking* (5 cm ... 0) Using magnetic forces

The most complex scenario includes all five phases, starting from Phase 1 *Orbit Manoeuvre*. In this scenario, all phases are run through sequentially one after the other. But note: the focus of the project is docking, so we will start with simpler scenarios. Orbit manoeuvres will only be tested at the end of the mission, if we still have enough fuel. Because of the limited fuel, we will not allow the satellites to get further than three kilometres apart. The orbit manoeuvres are calculated by operators on the ground. They are a combination of attitude control and firing the main engine to change the orbit of both satellites so that they come to a point closer than about 100 meters to each other. From this point onwards, the *Long-Range Approach* phase continues.

In the transition from *Long-Range Approach* to *Close Approach* phase, attitude control and main propulsion are also used, but these manoeuvres are not pre-calculated. For position determination, not the orbit parameters but the relative distance between the two satellites is used. In this short relative distance between the satellites, the complex orbit mechanics can be reduced to linear relative dynamics such as the Hill-Clohessy-Wiltshire equations. This reduction in complexity enables the calculation of manipulated variables for the attitude and position control of the further approach autonomously on board the satellites. The time window of the manoeuvre is limited, however, because otherwise the simplified relative dynamics model deviates too much from the real orbital mechanics, resulting in a too large "perturbation" for the autonomous approach of the satellites. The relative position is determined at this relative distance (< 100 m) using radio ranging. For radio ranging we use two ultra-wideband radio transceivers per satellite, which are a secondary radar system that can determine the distances with an accuracy of 5 cm. The modules are mounted as far apart as possible on the satellite. With 2x2 distance measurements we can determine (roughly at first) the distance and direction of the partner satellite. The relative attitude is determined using star sensors. With this information, both satellites can change their attitude so that the docking ports face each other. Additional active and passive optical markers such as LEDs are mounted around the docking ports of both satellites. These enable a camera installed on the side of the docking port, when the satellites are aligned with each other, to determine the relative position and relative attitude more accurately. Furthermore, the cameras will record the docking process and, under the right lighting conditions, could give a relative position estimate based on the 3D satellite model even without a direct view of the markers. If the satellites are correctly pointed towards each other (docking ports face each other), then the close approach begins. For this, a 3D cold gas propulsion system is used, which has nozzles in 6 directions. With this nozzle system we move the satellites towards each other while the docking ports face each other.

Below a distance of one meter, the *Finale Approach* phase begins. This phase is similar to the *Close Approach*, but only with optical pose determination by the cameras and only with fine position corrections. The docking mechanism works magnetically. From this point on, powerful electromagnets are activated.  Due to the small relative distance, we no longer expect any major orbital disturbances. As a result, the magnets will attract each other, the satellites will be mutually pulled towards each other and the satellites will be well aligned with each other. This continues until docking is complete. We have to take extra care to control the magnetic forces to limit the approach speed to a predefined value, which is a function of the relative distance as indicated in Figure 2. At the end of the approach, in the docking phase we shall have a very low relative speed to avoid damages due to collisions.

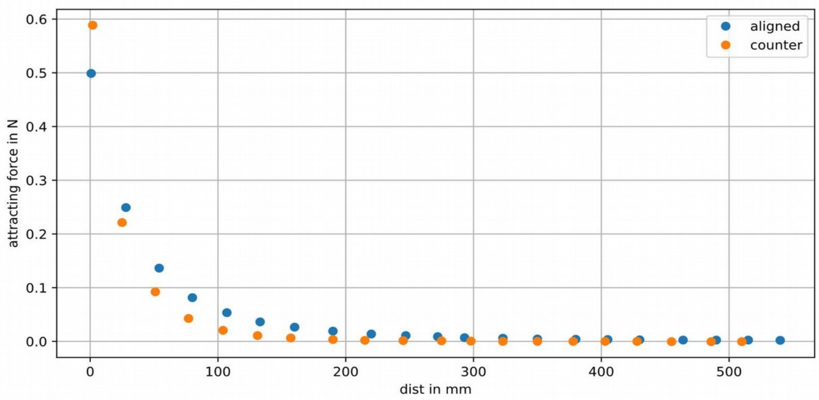


*Figure 2: Magnetic forces as function of the distance between the satelites.*

## 4.Mission Phases

As said before, initially, the satellites fly docked together. After LEOP and stabilization, we test these phases gradually. First, the satellites are separated, and before they have flown further than 5 cm apart, we test the final approach. In the next test, we let the satellites drift apart to about 50 cm and repeat the final approach and docking exercise. The next step is to allow the satellites to drift 5 meters, and from there we test the close approach until docking.  Then the same test is repeated at 10 meters. The next test is to let the satellites drift up to 100 meters apart and then start the long range approach to docking. And at the end of the mission, we let them drift up to a maximum three kilometres apart and then we test the whole procedure. After each step, we adjust the parameters based on the telemetry and optical feedback.

## 5. Challenges

The following challenges must be mastered:

- Determination of the relative position to each other with an accuracy of a few mm
  - Optical Tracking using Reflective and LED-Markers
  - Radio ranging + multidimensional scaling for a relative position determination
  - Lidar distance measurements
- Determination of the relative attitude to each other with an accuracy of less than one degree
  - Star camera with a new algorithm developed by us + Communication
- Relative orbit manoeuvres
  - Novel complex calculations
  - Distributed control
- Relative position control (Distributed control)
- Complex combined attitude and orbit manoeuvres
  - Wide approach (orbit mechanics)
  - Close approach (alternating attitude and orbit manoeuvres)
  - Final approach (propulsion + attitude control)
  - Docking (strong electro-magnetic docking port + attitude stabilization)
- Many boundary conditions for the manoeuvres, just before docking must be achieved:
  - Distance = 0
  - Relative velocity = ~ 0 (no collision)
  - Relative attitude must fit (Same inertial Attitude)

## 5. Satellite Interfaces

For all these operations the satellites have to communicate constantly with each other. They have to interchange radio ranging measurements, their inertial attitude, results of the optical tracking, lidar measurements and computed relative speed. We will implement an inter-satellite radio link using the normal WiFi protocol. This will work only in a proximity lower than 200 meters. For longer distances we have to use the ground station as relay station. But for such "big" distances the inter-satellite communication is not crucial.

For docking, a reliable magnetic docking port with corresponding sensor technology must be designed for a 3-U CubeSat. A CAD model of the magnetic docking interfaces is shown in Figure 3. The port's active magnets should influence the satellite's attitude and orbit manoeuvres as little as possible and still provide stable guidance and connection in the near field. Therefore, when we activate the powerful magnets of the docking port, both satellites have to be  aligned along the magnetic field of the earth, and they have to be looking to each other in the same direction. This is a difficult orbital and attitude manoeuvre which is more simple above the equator. Close to the poles of the earth relative deviation of the magnetic lines of the earth move to fast.

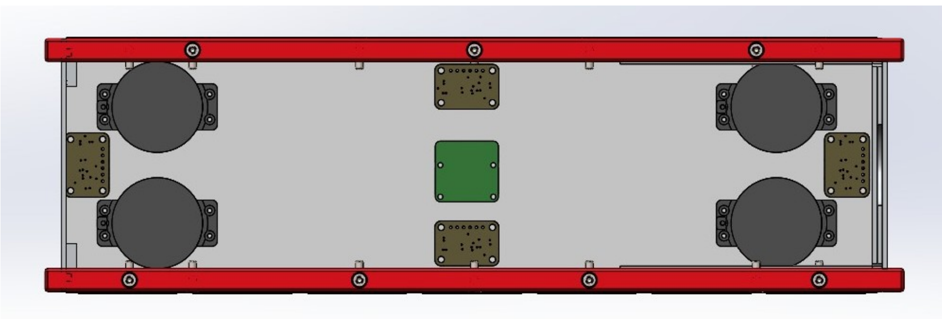

*Figure 3: Docking side of both satellites, showing the 4 electromagnets.*