DEVELOPMENT OF A LOW COST, MEDIUM ACCURATE 2-AXES POINTING MECHANISM FOR SMALL SATELLITES

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1. ABSTRACT

This paper deals with the development of a mechanism for steering intersatellite-link (ISL) RF antennas. It is expected that such antennas will gain importance in future telepresence and formation flight missions. BayernSat, a micro-satellite mission designed at the Institute of Astronautics (LRT) at Munich, will use such a link and is therefore the baseline application for the investigations.
A market analysis of existing mechanisms, as found basically on geostationary satellites, shows that they all attach highest importance to precision steering. Another character of all existing mechanisms is their mounting outside of the satellite, often between the satellite body and the antenna. For an application on small satellites such as BayernSat, they are however overengineered or increase the envelope of the overall microsatellite to an unacceptable extent.
Therefore, an in-house decision was made to develop a 2-axes mechanism for the baseline application on BayernSat regarding the special needs of such small satellites in general. To make this mechanism applicable for the growing market of micro-satellites it has to be small and compact enough to fit into reasonable envelopes within satellites of this class. The mechanism puts emphasis on reliability despite low cost, rather than precision and is mounted inside the satellite. All sensitive parts, such as motors are therefore protected from the harsh environment by the satellite's structure.
Due to the high beam width of flat S-band antennas as baseline application, the steering of such an antenna implies only medium precision requirements on the tracking mechanism. This easing of the requirements yields many advantages.
The concept of the steering mechanism has been evaluated by a breadboard model, which has been built at the LRT. In combination with an S-band antenna and a 3-axes attitude simulator, which are both currently under construction at LRT, an efficient testbed will be available. By establishing and maintaining radio links from ground to satellites in space, this testbed will be able to demonstrate the functionality of an entire intersatellite link system.
Finally, the spin-off potential of the newly developed mechanism will be investigated. It is considered that this mechanism could be utilized for many medium precision steering applications, such as the adjustment of solar arrays or camera and scientific instrument steering.

2. INTRODUCTION

Since March 2004 the project BayernSat [1] is the basis for all satellite technology activities at the Institute of Astronautics (LRT). BayernSat is a cubic satellite with the dimensions of (50 cm)³ and a weight of about 50 kg. With these dimensions BayernSat belongs to the family of micro-satellites. The primary mission goal of BayernSat is to demonstrate Telepresence (i.e. a technology that enables a human operator to have the feeling as to be present in a remote environment) in space. This will be based on using a geostationary satellite as a relay for establishing a real-time link to control a Low Earth Orbit satellite.

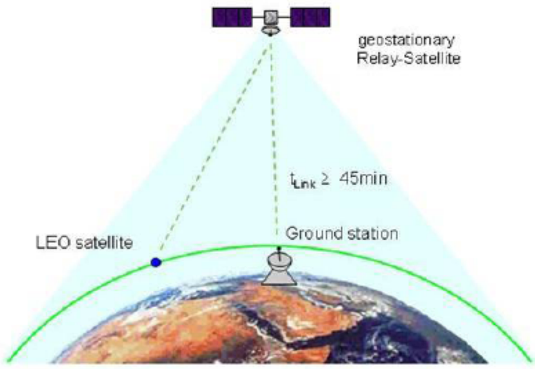

FIG 1. Improvement of acquisition time by a relay satellite

Therefore the access to the LEO satellite is not limited to the visibility to the satellite, but is of the order of 45 minutes [2].

There are several sub-tasks involved in this Telepresence project:

- The real-time scenario requires a reconfiguration of the CCSDS (Consultative Committee for Space Data Systems) protocol standard [3]
- The signal roundtrip time has to be reduced to values less or equal than 0.8 sec [3]
- An flat S-band antenna for use on small satellites is developed at the LRT [4]
- For maintaining the link between BayernSat and the geostationary satellite steering of the antenna is necessary.

Steering of the antenna therefore is one key technology for a Telepresence link and will therefore be used as a baseline for the following considerations. Steering shall be realized by a low-cost mechanism (<30000€) with medium accuracy (±2°).

3. MARKET ANALYSIS OF EXISTING MECHANISMS

As a first step the available commercial steering mechanisms for ISL applications were evaluated. It was investigated whether the existing mechanisms can be

applied for steering a flat antenna on a micro-satellite such as BayernSat.
Analysis showed that most existing mechanisms attach highest importance to precision, as they are normally used for Ka-band antennas on geostationary satellites. This precision implies:

- Expensive components due to highly accuracy
- Small tolerances
- Small angular rates
- Limited angular ranges.

Another problem of existing mechanisms is their size. No mechanism designed for steering small and light antennas as the BayernSat S-band antenna could be found.
Another conflict derives from the concept of most mechanisms that they are all mounted outside of the satellite situated between the satellite body and the antenna. But the distance between satellite body and antenna is not only defined by the mechanism size, but also by the kinematical concept. To use Telepresence efficiently, the antenna has to be able to point all directions within a half sphere (90° elevation, 360° azimuth). Using gimbal mechanisms, this pointing can only be realized by mounting the antenna at a distance of at least half the antennas extent (see FIG 2). For the 40 cm x 40 cm antenna of BayernSat this would lead to a spacing of more than 20 cm between satellite body and the antenna.

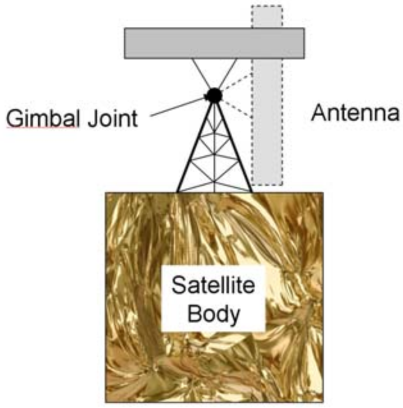

FIG 2. Antenna spacing with gimbal design

This spacing might be acceptable for large satellites with small antennas, but for small satellites they highly increase the satellite's overall size and therefore drive costs and lower the chances for piggy back flight opportunities, which is not acceptable.

4. PRELIMINARY CONSIDERATIONS FOR STEERABLE S-BAND ANTENNAS ON SMALL SATELLITES

As mentioned before, BayernSat is a cubic satellite with the size of 50 cm. The size of the antenna derives from the requirements for S-band reflectors as a square plate of 40 cm at a height of 7 cm and to fit flat on one side of the satellite. The steering mechanism needs to be adapted to this setup, so a two-axes design was decided with reduced requirements for tracking precision, due to the large beam width of the antenna [4].
The requirements reduction has various advantages:

- The precision requirements of the components are low, which lowers the prizes on component level.
- Bearing clearances can increase accuracy. Designing double sliding surfaces (e.g. bushings with inner and outer sliding coatings) can imply redundancy.
- Thermal deformations can be widely neglected (as long as they do not impact the operation of the mechanism).

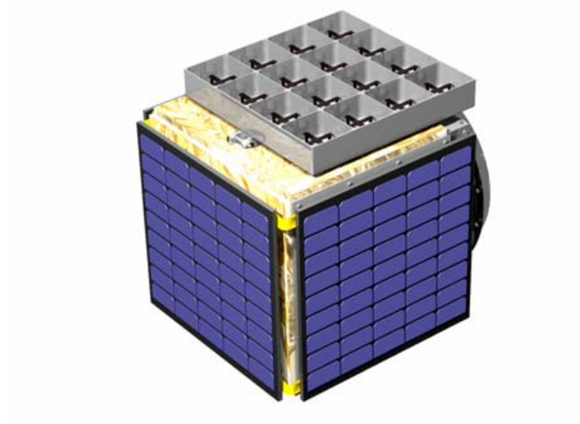

FIG 3. BayernSat with its S-band antenna

That the mechanism houses most of the components inside the satellite casing implies additional advantages:

- The antenna can be stored fitting flat to the satellite (one of the main drivers for development of flat panel antennas) with only a very small spacing.
- Sensitive components (actuators, gears, electronics) inside the satellite are protected from the harsh environment (radiation, temperature). So, apart from vacuum these influences can be widely neglected. This lowers the requirements for the components, such as motors, and eases eventually necessary qualification tests.

5. STEERING MECHANISM DETAILS

5.1. Kinematic Concept

The BayernSat mission drives the requirement for tracking targets within a half-sphere above the mounting surface of the antenna. This required half-sphere for pointing can be realized by a 2-axis rotation (azimuth ±180°, elevation 0-90°)
Because of rotation of the complete elevation drive section, a rotationally symmetric envelope for the components inside the satellite is desired. This drive section shall ideally be designed as a thin cylinder aligned with the rotation axis of the azimuth motion.

5.2. Design of the Breadboard Model

The mechanism consists of two separately driven sections. Both of them are actuated via stepper motors. The following subchapter describes the design of the breadboard model.

5.2.1. Elevation Stage Design

The elevation stage elevates the antenna from 0° to 90°. The kinematical concept is based on an approach using a linear actuator and three bearings as depicted in FIG 4.

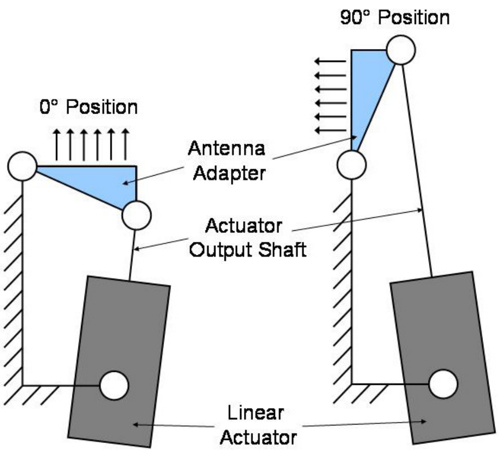

FIG 4. Kinematical Concept of the Elevation Stage

In a first model the antenna is mounted on the antenna adapter, which is mounted pivotingly via bearings to the structural parts. The antenna adapter is driven by a linear ball screw actuator. Therefore the output pin of the actuator is connected to the antenna adapter with a spherical bearing. The actuator's case is connected to the structure also with bearings. When driving the actuator, the antenna adapter is pushed upwards. Due to the constraints in the degrees of freedom of its bearings, it rotates towards its 90° position (anti-clockwise in FIG 5). During actuation, the spherical bearing, which connects the output pin of the actuator with the antenna adapter travels on a circular arc around the bearing between structure and antenna adapter. Therefore the actuator has to be able to tilt to compensate this action. This is realized by a bearing between the case of the actuator and the structure.

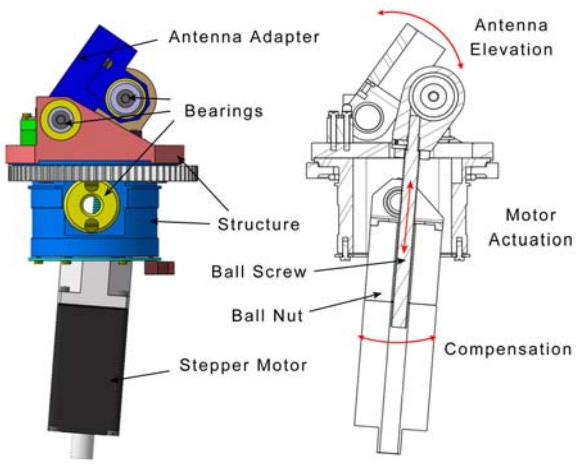

FIG 5. Elevation Section Design

To keep the complexity of this stage low, no encoder for the position is foreseen. Instead a stepper motor is used, which is designed strong enough so that no steps will be skipped. However, reference switches for the upper and lower position of the stage are integrated, which are also used for initialization of the stage when errors appear. Because of the kinematical complexity, the elevation stage does not display a linear behavior (see FIG 6). At each position of the actuator, the transmission ratio is different. However, the ratio can be easily described by a trigonometrical treatment. This non-linear behavior has to be taken into account in the control algorithm, to ensure constant angular speeds of the antenna by proper variations in the actuator speed.

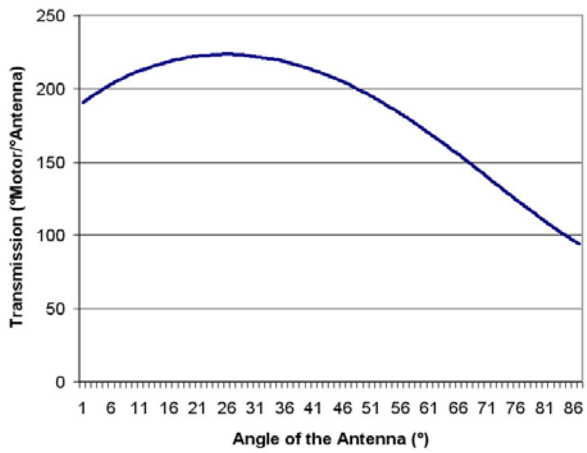

FIG 6. Transmission Ratio for the Elevation section

5.2.2. Bearing Design

As mentioned before, the modest requirements for accuracy permit to increase the reliability of the mechanism. Therefore, backlash in the bearings is intentionally designed, as well as redundancy within the bearings.

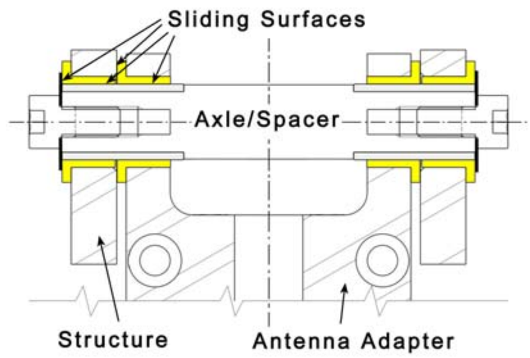

FIG 7. Redundant Bearing Design

In each bearing, each of the connected parts features a friction bearing bushing (see FIG 7). Those have sliding contact to an axle or a bolt, holding the bearing together. If one of the sliding surfaces in one of the bushes fails, the function can therefore be taken over by another one.

5.2.3. Azimuth Stage Design

The Azimuth stage incorporates the elevation stage revolvable in an outer structure. In the breadboard model two ball bearings are used. The azimuth actuator transmits force via a gear, which is built by the driver and a cogwheel mounted to the elevation stage (FIG 8).

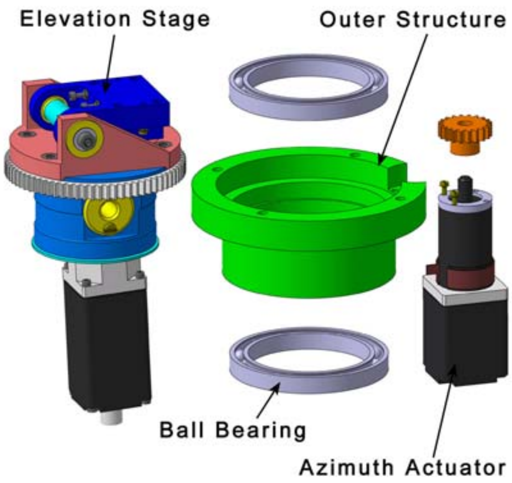

FIG 8. Exploded View of Azimuth Stage

5.3. Breadboard Data Specification

The specifications for the breadboard model of the steering mechanism are summarized in the table below.

TAB 1. Specifications of the BB Model

Parameter	Value	Comment
Mass	1,5 kg	Mainly due to heavy motors
Outer diameter	98 mm	
Height	141 mm	0° Position
Envelope volume	500 cm³	Rotational envelope
Elevation torque	> 5,6 Nm	90° Position
Azimuth torque	5,4 Nm	
Elevation backlash	±1,5°	
Azimuth backlash	±0.5°	

FIG 9. Breadboard model built at LRT

6. VERIFICATION & TEST

For sufficient verification of the mechanism in the application, a test bed and the necessary controller for the mechanism have been developed at the Institute of Astronautics.

6.1. The Test Bed

For verification and test of the antenna system (i.e. ISL-antenna and pointing mechanism) a test bed was developed. Using an existing S-band antenna turn table and adding an additional degree of freedom, a 3 degree of freedom satellite attitude simulator has been constructed [5]. It is located on the roof top of the institute's building and thus features unimpeded sight to outer space. The simulator with the attached satellite mock-up and the antenna system will simulate a freely movable satellite in a Low Earth Orbit (see FIG 10), which establishes a continuous link to the geostationary relay satellite ARTEMIS.

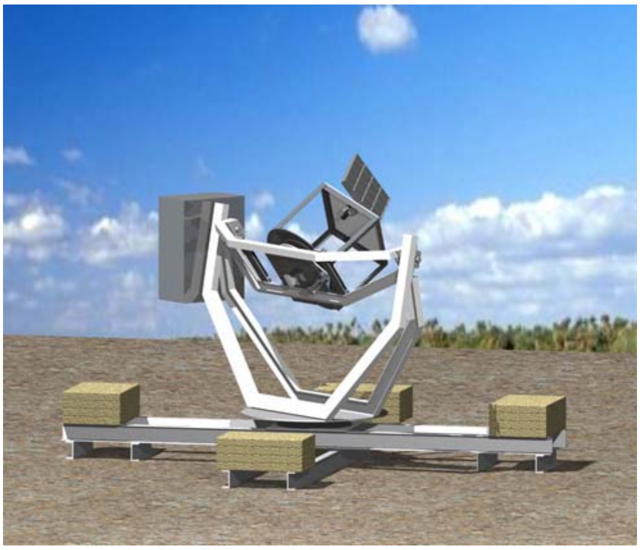

FIG 10. Telepresence demonstrator on roof-top of LRT

FIG 11 shows the schematical setup of the test bed. The satellite attitude simulator itself is coupled to a PC (Ground Station Monitoring & Control) which steers the simulator's 3-DOF motion. On the PC an orbit simulation program (STK, Satellite Tool Kit) is running, which generates attitude data. It will simulate different kinds of orbits with different attitude constraints e.g. general nadir pointing or sun-synchronous. The data will be converted into Gaussian angles, considering the relative angular position of both satellites. For this conversion it is further important that the satellite mock-up with the antenna system is not orbiting as the simulated LEO satellite, but has a fixed position in the Earth Centered Fixed (ECF) coordinate system. With the given Gaussian angles the simulator is actuated and the simulator affirms in turn its angular position. The following subchapter will clarify this problem in detail.
The second PC (On-board Computer), which handles the antenna pointing, only receives the pseudo satellite attitude data and correspondingly controls azimuth and elevation of the antenna pointing mechanism. This way the antenna system steered by a pointing algorithm, which is fed by data on the ARTEMIS position, will autonomously compensate the satellite attitude and maintain the link

between the ground antenna and the relay satellite in space. With this the intersatellite communication link is maintained while the attitudes of two satellites change relative to each other.
The Telemetry & Telecommand (TMTC) computer simply handles the communication path, i.e. data processing, conversion and transmission.

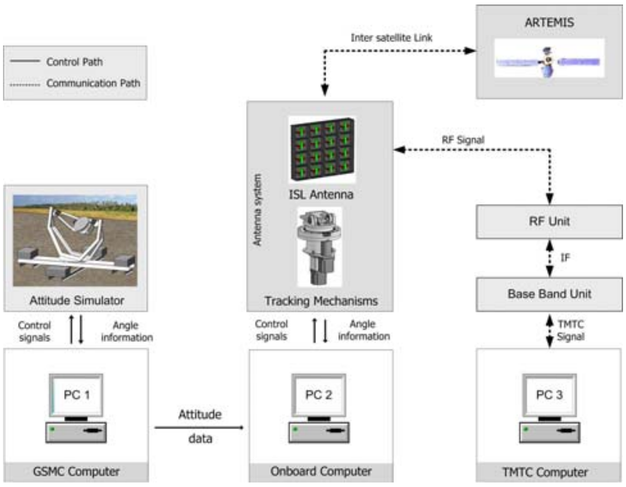

FIG 11. Test bed setup

6.2. Pointing Algorithm

In the following the pointing algorithm of the antenna system is explained. The purpose of the algorithm is to point the antenna such that a continuous link with ARTEMIS is established.
It is based on the two-line elements (TLE) of the communicating spacecrafts. It is trivial to derive the radius vectors of the satellite, $\underline{r}_{sat}$, and ARTEMIS, $\underline{r}_{art}$, in an Earth-centered Earth-fixed coordinate system, denoted by XYZ (see FIG 12). Thus, the vector between both satellites is

$$\underline{d}_{\mathrm{isl}}^{(XYZ)} = \underline{r}_{art}^{(XYZ)} - \underline{r}_{sat}^{(XYZ)}$$

It may be transformed into the radial satellite coordinate System RSW by means of

$$\underline{d}_{\mathrm{isl}}^{(RSW)} = \underline{\underline{A}}(TLE_{sat}) \cdot \underline{d}_{\mathrm{isl}}^{(XYZ)}$$

The RSW system with its R-axis aligned to the radius vector, W normal to the orbital plane and S completing the Cartesian coordinate system (in principle pointing towards velocity for a weakly elliptical orbit) is moving with the satellite. This has the advantage that by having sufficient information of the on board Attitude and Orbit Control System (AOCS) about the attitude of the satellite's body axis (denoted by xyz) with respect to RSW, the ISL vector can be transformed into the body system. This can for example happen due to a series of Euler angle rotations.

$$\underline{d}_{\mathrm{isl}}^{(xyz)} = \underline{\underline{A}}_1(\psi) \cdot \underline{\underline{A}}_2(\theta) \cdot \underline{\underline{A}}_1(\varphi) \cdot \underline{d}_{\mathrm{isl}}^{(RSW)}$$

The intention of the previous coordinate transformations was to obtain the direction of ARTEMIS $\underline{d}_{\mathrm{isl}}$ in the satellite body coordinates, in which the attitude of the ISL-antenna is well known.

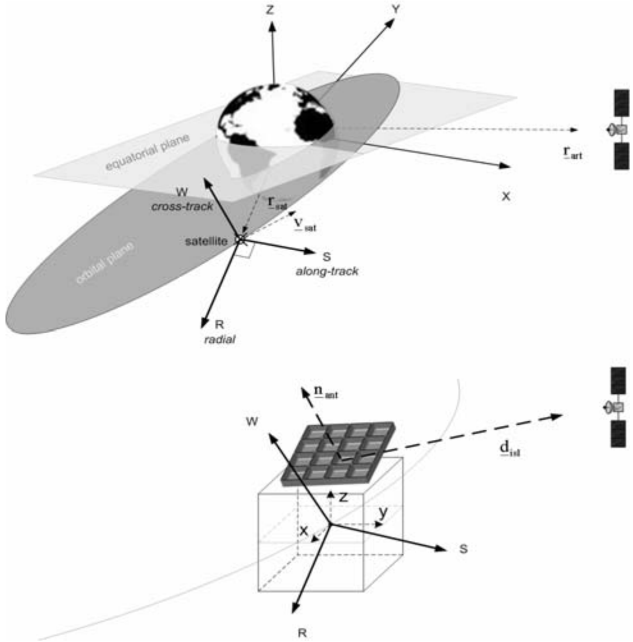

FIG 12. Sketch of the used coordinate systems

The antenna can be considered as a rotating plane, the attitude of which can be described by the normal vector $\underline{n}_{\mathrm{ant}}$ of the antenna, with azimuth ε and elevation δ. The reference orientation of the antenna is defined as $\underline{n}_{\mathrm{ant\_0}}=(0,1,0)^T$, which means that the normal vector parallel to the y-axis of the body system. So any attitude state can be expressed in dependence of azimuth and elevation of the mechanism:

$$\underline{n}_{ant} = \underline{\underline{A}}_3(\varepsilon) \cdot \underline{\underline{A}}_1(\delta) \cdot \underline{n}_{ant\_0} = \begin{bmatrix} \sin\varepsilon \cdot \cos\delta \\ \cos\varepsilon \cdot \cos\delta \\ -\sin\delta \end{bmatrix}$$

Obviously, the target attitude is achieved if the antenna normal vector and the direction vector are parallel to each other

$$\underline{n}_{\mathrm{ant}}(\varepsilon^*, \delta^*) = \underline{d}_{\mathrm{isl}} \quad \text{or}$$
$$\underline{n}_{\mathrm{ant}}(\varepsilon + \Delta\varepsilon, \delta + \Delta\delta) \times \underline{d}_{\mathrm{isl}} = 0$$

where ε and δ are known and $\Delta\varepsilon$ and $\Delta\delta$ are the variables which have to be actuated by the controller of the mechanism.

7. ENHANCEMENTS FOR THE PROTOTYPE

The performance of the mechanism could be verified by the first breadboard model. Also reliability seems to be high enough, because of the low complexity of the mechanism. However, further improvements has to be undertaken to qualify the mechanism for space. The main steps for overcoming the mid-maturity valley of death [7] are the following:

1) Improvement in performance (transmission ratios etc.)
2) Weight optimization
3) Employment of space-qualified materials and

components
4) Qualification Tests
5) Prove of on-orbit performance

7.1. Performance and Weight Improvements

Performance and weight have been improved while the breadboard model was manufactured and verified. The new design shows smaller dimensions, but also a much more evenly distributed transmission ratio.

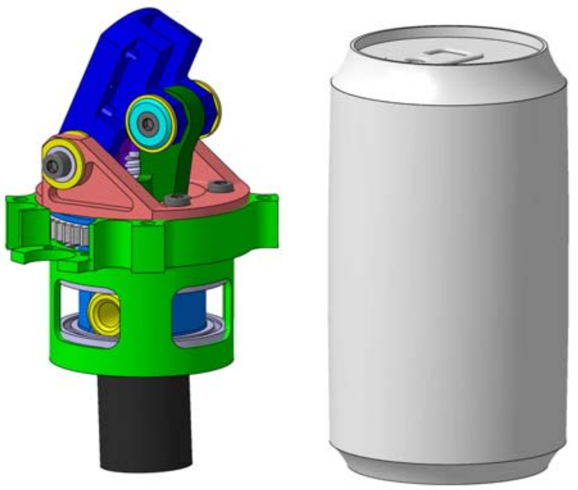

FIG 13. Optimized version of the steering mechanism (displayed without azimuth drive, next to a soda can to illustrate its size)

The new design as shown in FIG 13 was attained by a change in the design of the linear actuator, tighter packaging of the components and removal of material with the aid of FEM analyzes.

7.2. Application of Space Qualified Materials and Components

For the breadboard model, so far standard aluminum and brass alloys have been used. Low prized commercially available stepper motors and bearing bushes have also been used, which are not qualified for space.
For the prototype more sophisticated technology will be used. However, emphasis of the mechanism shall still be put on low cost. For instance the bearing bushes will be used as in the model, after applying qualification tests on them. Critical components, such as motors and ball bearings, however have to be replaced by space qualified components.

7.3. Qualification Testing

Fortunately, the Institute of Astronautics possesses a sophisticated qualification infrastructure. Qualification will be performed using the in-house thermal-vacuum chamber facilities and vibration test devices.

7.4. Functional On-Orbit Verification

It is anticipated to perform a on-orbit qualification test for the mechanism. This is essential for obtaining high technology readiness levels [8], which is mandatory for commercialization. BayernSat in fact is a technology verification mission for Telepresence. Therefore BayernSat could also adduce the space qualification.

8. OTHER APPLICATIONS

The steering mechanism is developed primarily for targeting an antenna to another satellite. However, target pointing is a very general issue. So far several applications with similar requirements have been surveyed.

8.1. Camera or scientific instrument pointing

The mechanism is also capable of pointing small cameras or scientific instruments to specific targets. Therefore, the spacecraft does not have to perform attitude changes due to the scientific payload. So the mission resource planning (lighting condition, power, propulsion) is not or only weakly dependent on the requirements of the spacecraft due to attitude. This plays an important role for satellites which carry multiple payloads (e.g. EnviSat) or if the payload is small and low cost compared to the mission that it is considered as secondary payload.

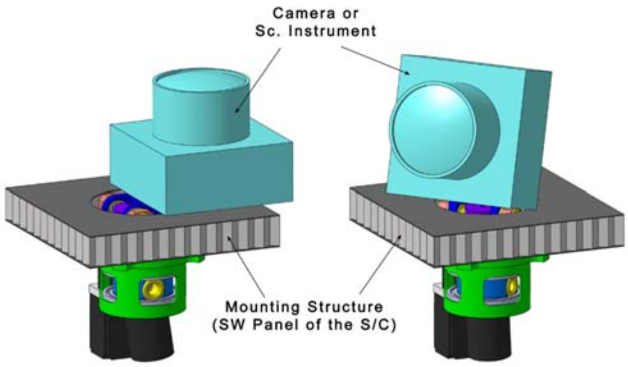

FIG 14. Pointing of a camera

8.2. Solar Array Pointing

The developed low-cost steering mechanism allows also small satellites, for which power is always a critical resource, to effectively point solar arrays towards the Sun. FIG 15 depicts how a one-sided solar array (solar cells only on one side of the array) can be illuminated by the sun perpendicularly for almost all attitudes of the satellite bus with this mechanism.

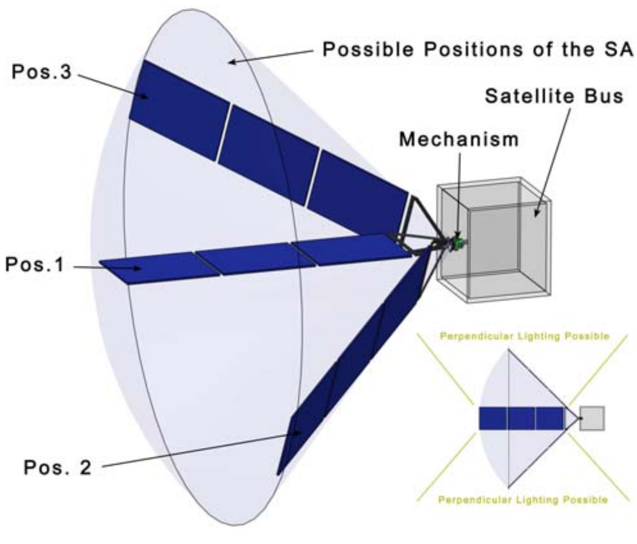

FIG 15. Steering positions of a one-sided solar array for perpendicular lighting of the sun

9. CONCLUSION

We have developed a 2-axes mechanism to point an RF antenna to another satellite in space. This is based on an improved kinematical concept, which makes the mechanism applicable for small satellites. Emphasize has been put on not to over-engineer this mechanism, so that the costs will not impede low-cost applications, yet to be qualified for space. The breadboard model of the mechanism showed satisfactory performance. Using a test bed for an end-to-end intersatellite communication link, the mechanism is foreseen to perform also in the overall link setup. For further development to the prototype cooperation with a space industry partner for pushing the technology further towards high readiness levels is desired, or even to develop a commercially available product.

10. REFERENCES

[1] BayernSat - A Real-Time Communication-Architecture for Interactive Earth Observation via Geostationary Inter Satellite Link for Small Satellite Systems; Jürgen Letschnik, Matthias Raif, Kristian Pauly, Ulrich Walter; 5th IAA Symposium on Small Satellites for Earth Observation, Berlin, 2005

[2] BayernSat - How to Utilize Relay Satellites for Real-Time Data Acquisition on Small Satellites; Matthias Raif, Jürgen Letschnik, Kristian Pauly, Ulrich Walter; 5th IAA Symposium on Small Satellites for Earth Observation, Berlin, 2005

[3] The Consultative Committee for Space Data Systems (CCSDS); About CCSDS http://www.ccsds.org/.

[4] LISA – Lightweight Inter-Satellite Antenna; Robert Lundin, Ulrich Walter; Deutscher Luft- und Raumfahrtkongress 2006

[5] Construction and Realization of a Low-Cost Satellite Attitude Simulator Concept; Enrico Stoll, Jürgen Letschnik, Manuel Czech, Ulrich Walter; ICSSC, San Diego

[6] Concept of a Low-Cost Satellite Attitude Control Simulator Based on an Antenna Turntable; Jürgen Letschnik, Enrico Stoll, Manuel Czech, Ulrich Walter; ETC 2006, Garmisch

[7] To Develop the World's Most Advanced Miniature Satellites; Caneus NPS Inc. and AAC; www.csba.se /activities/recap/060509/caneus.nps.pdf

[8] Technology Readiness Levels, A White Paper; John C. Mankins; Advanced Concepts Office, Office of Space Access and Technology, NASA

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