Electro Active Polymers as a Novel Actuator Technology for Lighter-than-Air Vehicles

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ABSTRACT

In this paper the worldwide first EAP actuated blimp will be presented. It consists of a slightly pressurized Helium filled body of a biologically inspired form with Dielectric Elastomer (DE) actuators driving a classical cross tail with two vertical and horizontal rudders for flight control. Two versions of actuators will be discussed: The first version consisted of "spring-roll" type of cylindrical actuators placed together with the electrical supply and control unit in the pay load gondola. The second version consisted of a configuration, where the actuators are placed between the control surfaces and the rudders. This novel type of EAP actuator named "active hinge" was developed and characterized first in the laboratory and afterwards optimized for minimum weight and finally integrated in the blimp structure. In the design phase a numerical simulation tool for the prediction of the DE actuators was developed based on a material model calibrated with the test results from cylindrical actuators. The electrical supply and control system was developed and optimized for minimum of weight. Special attention was paid to the electromagnetic systems compatibility of the high voltage electrical supply system of the DE actuators and the radio flight control system. The design and production of this 3.5 meter long Lighter-than-Air vehicle was collaboration between Empa Duebendorf Switzerland and the Technical University of Berlin. The first version of this EAP blimp first flew at an RC airship regatta hold on 24th of June 2006 in Dresden Germany, while the second version had his maiden flight on 8th of January 2007 in Duebendorf Switzerland. In both cases satisfactory flight control performances were demonstrated.

Keywords: Dielectric Elastomer Actuator; Lighter-than-Air Vehicle; Blimp; Flight Control Systems

1. INTRODUCTION

Electro active polymers (EAPs) are promising material systems as actuators in active structures, where large deformations and low weight are required. Especially in Lighter-than-Air vehicles the structural and systems components have to be extremely light [1, 2]. In the last decades various concept studies have been performed for stratospheric platforms, which are interesting alternatives for land-based networks as well as satellites in telecommunication, reconnaissance and observation. Fig. 1, [3-9]. EAPs transform electrical energy directly to mechanical work and produce large strains. For example dielectric elastomers (DE) were recently shown to have good overall performances. Forces per area of 16.2 MPa, free area strains of 215% and specific elastic energy densities of 3.4 J/g could be shown, [10]. A DE actuator is basically a compliant capacitor, where a passive elastomer film is sandwiched between two compliant electrodes. When an electrical voltage is applied, the electrostatic forces arising from the charge displacement on the electrodes squeeze the elastomer film. This electrode pressure mechanically loads the polymer film. Because such elastomers are essentially incompressible the area of the capacitor is enlarged. As soon as the voltage is switched off and the electrodes are short-circuited the capacitor contracts back to its original shape. With the DE actuators developed at Empa Duebendorf in the last years a suitable technology is nowadays available to design active elements which can serve as actuators for flight control in airship.

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In this project two types of DE actuator were used: the first type was the well known “spring-roll” actuators developed earlier at Empa. These actuators were expected to represent a low risk version of the EAP driven blimp, because the specific characteristics of these actuators were well known. The second type were DE actuators which are fully integrated between the slightly modified control surfaces and the rudders. The performances of these “active hinge” called actuators were not known. Therefore as a first step theoretical predictions of such a configuration based on newly developed material models were performed. The second step was to built functional models and characterize them under clearly controlled laboratory conditions. Finally both types of actuators were integrated in a blimp and tested according to the flight control specifications of a 3.5 m long, 0.9 m in diameter large conventionally propelled indoor flying airship. Some development tests where carried out with parts of this EAP blimp or even with the whole system:

1) flight trials with the first version and some qualitative estimations of the flight performance
2) an ultimate load test for a quarter of a cross tail with an active hinge in a wind tunnel
3) wind tunnel testing for the whole blimp (second version) with flow visualization and loads measurements
4) flight trials with the second version with qualitative and semi-quantitative flight performance measurements

In the following chapter the technical specifications for the whole system and the actuators in special will be analyzed and discussed.

2. SYSTEM REQUIRMENTS

2.1 Weight and balance

The main goal was to realize a self balanced airship which was able to fly in aerostatic equilibrium in typical European atmospheric condition (10 – 30°C, min. 950 hPa air pressure, 10 – 90% rel. humidity). The aerostatic equilibrium is satisfied if a 1 m^3 volume is filled with helium and the total weight of the airship is less than 1 kg. In a preliminary weight and balance analysis a 3.5 m long, 0.9 m large body was estimated to produce enough lift to hold approx. 1 kg of total weight. The main weight components and the total lift are listed in table 1.

Table 1. Preliminary weight and balance analysis.

Weight and balance	
Structural weight	
Envelope	240 g
Gondola, with engines, electr.	360 g
Cross tail	217 g
Bowden wires	15 g
Power supply (accumulator)	36 g
Balance weight: (accumulator)	95 g
Total aerostatic lift:	965 g

The balance weight was a variable to be defined immediately before flight to find the force equilibrium in the vertical direction. A range of ±10% of total lift was judged to be enough for compensating local atmospheric differences to the design case. The position of the gondola was defined by the equilibrium of moments and was estimated to be 1.15 m behind the tip of the airship. The exact balance could also be adjusted immediately before flight by positioning the balance weight.

2.2 Electromechanical compatibility

Very early in the project the electromagnetic compatibility of the radio control (RC) system on one side and the electrical supply and control system for the DE actuators on the other side had to be checked. A fully digital system of the RC system was necessary to be compatible with the high voltage signal generation used.

2.3 Structural integrity

In all flight conditions the structural stability and integrity had to be fulfilled. The lifting body had his form by an internal pressure in the gas volume of approx. 350 Pa. This internal pressure was enough also to hold the gondola and the cross tail in its correct orientation.

The structural integrity of the gondola and the cross tail was reached by a conventional lightweight construction, but using an extremely light material: Depron ®, a polystyrol foam. In the gondola the most concentrated load transfers were from the engine mounted on carbon reinforced small tubes fixed in a main spar, built from a Depron plate sandwiched between to CFRP shells. The horizontal and vertical tailplanes as well as the rudders were made from Depron ® spares, ribs and skins.

All the dimensioning of the systems was based on a maximum flight speed of 10 m/s and a cruising speed of 5 m/s. The flights were restricted to indoor environment, e.g. without any turbulences or wind.

2.4 Performance requirements for the DE actuators

The flight control design consists of variable trust generation for acceleration and deceleration and a conventional cross tail with horizontal and vertical rudders. The technical specification for the actuators driving these rudders was based on a maximal (ultimate) speed of 10 m/s and a maximum rudder deflection angle of ±30°. Using aerodynamic loads analysis and the geometry of the cross tail, a maximum hinge moment of 1.5 N*cm was calculated.

3. DEVELOPMENT OF SUBSYSTEMS AND SYSTEM INTEGRATION

The development of the blimp was a collaboration between the Technical University of Berlin (TU Berlin) and Empa. TU Berlin was responsible for the design, development and production of the envelope and the cross tail, see Fig 2. Empa was responsible for the gondola including the control unit, propulsion and the actuators for driving the control rudders see Fig 3.

3.1 The body and tail

In the first part of the work the concept of a blimp with a fish-like body and conventional cross tail was developed. This blimp has a volume of about $1m^3$ and a length of 3,5m. It consists of a slightly pressurized helium filled body of a biologically inspired shape with minimum drag characteristics, see Fig. 2. This form has been developed based on detailed analysis and experimental testing of various types of Penguin birds by Bannasch [11]. With water channel and wind tunnel tests an excellent drag coefficient of such forms could be found experimentally. In addition these shapes show a very good compromise between low drag and high volume to surface ratio. While this ratio is important in the thermal energy management of the Penguins in the arctic environment, the same ratio is important in structural design of Lighter-than-Air vehicles. Therefore this optimized form found by the Penguin can be successfully adopted for a blimp design. The envelope was made of Nonex [12] which is a polymeric multilayer structure especially developed for Lighter-than-Air vehicles. It consists of nine layers, two helium-proof layers included, coated by aluminium on one side and polyethylene (PE) on the other side. This foil, developed by Aerostatix is an extremely helium-proof and nicely weldable foil with a thickness of 25µm.

3.2 Payload gondola with propulsion system and DE actuators

The payload gondola is a three quarter closed box made of Depron ® with one main spar in the centre. All the electrical equipment was placed within the gondola, except the power supply accumulator, which was fixed as an additional external payload, positioned as a balance weight. Two engines were mounted on a lateral carbon reinforced tube connected to the main spar. Only in the first version of the blimp the cylindrical actuators were also placed in the gondola. Special attention was paid to the electromagnetic systems compatibility of the high voltage electrical supply system of the DE actuators and the radio flight control system.

3.3 Control device

For controlling the EAP blimp a commercial radio control (RC) unit which is normally used for model airplanes or model helicopters was chosen, Fig. 4. It is equipped with control sticks for altitude control, direction control, and also for speed control.

The control device for the EAP blimp is situated in the payload gondola, see Fig. 3 and 4 and consist manly of four units: one for driving the blimp, one for steering the blimp, one for the electric power supply and one for the wireless communication with the RC unit, see Fig. 5.

For power supply the system, Lithium – Polymer (LiPo) accumulator is chosen. The benefit of the LiPo accumulator is the low weight associated with the high energy density. In cause of emergency the whole system could be cut of by the on/off switch next to the LiPo accumulator.

For the driver propulsion system two brushless direct current (DC) motors, with a power of 15W each and lightweight air-screws, was selected. The revolution speed of each brushless DC motor is controlled by a commercial brushless motor control unit which is connected to the remote control receiver (Fig. 5).

The steering systems for left/right and horizontal rudder are identical in construction. For that reason only one steering system will be described. As shown in Fig. 1, the control logic for left/right and horizontal rudder is next to the remote control receiver and connected together by wire. The remote control receiver provides a pulse width modulation (PWM) signal depending on the control stick position on the RC unit. The control logic transforms the PWM signal in a proportional DC voltage signal with a range of the voltage between 0V for no deflection of the rudder and 5V DC for the maximum (45°) deflection of the rudder. Two commercial DC/DC converters (Q50-5, EMCO High Voltage Corporation) are linked to the control logic. The output voltage of a DC/DC converter depends on the input voltage from the control logic and is in the range of 0V for minimum input voltage and 5kV for maximum input voltage from the control logic. Therefore, the EAP actor connected to the DC/DC converter expenses by supplying it with high voltage. The function is as follows:

When the EAP actor is supplied with high voltage it will be loaded and for that reason the actor expense. The expense depends on the high of the voltage which is indirectly chosen by the control stick on the RC unit.

After the stick on the RC unit is put in a lower position, the voltage from the DC/DC converter decreases. Now the EAP actor will be unloaded by the resistor R next to the DC/DC converter and the actor contracts (Fig. 5).

3.4 Control surface actuators

In the first version the well characterized cylindrical actuators developed earlier at Empa were chosen. There performance data are summarized in table 2. Due to durability reasons actuators of type 3 were chosen. These cylindrical actuators move a conventional rudder system. The cylindrical actuators operating according to the bionic principle of the muscle system are located in the gondola. One pair of actuators each is moving the rudders and the elevators, hence in total four actuators are necessary, as shown in Fig. 6. The forces of the actuators were transferred from the gondola by a Bowden wire (a wire that can transfer pushing and pulling forces) to the rudders.

Table 2. Performance of cylindrical actuators developed at Empa:

Performance of cylindrical actuators

Type	duarbility [cycles]	stroke [mm]	force [N]	work [mJ]	power [mW]	efficiency* [%]	weight [g]	diameter [mm]	length [mm]
1	400	25	10	130	140	3.5	17.5	12.25	110
2	500	23	9	120	80	3.5	14	10	110
3	30’000	17	8	55	60	3.5	11	9.25	110

Legend: * this is the electro-mechanical overall efficieny

In the second version of the EAP blimp a novel type of actuator was used on the same airship body, to move conventional rudders, see Fig. 7. Basically they consist of a pair of DE membranes hold apart by a passive hinge and integrated fully in the cross tail. The membrane are made from VHB 4910 from 3M prestrained to an end thickness of approx. 50 µm. The passive substructure was made from Depron ® material. This novel type of DE actuator named “active hinge” was developed and characterized first in the laboratory and afterwards optimized for minimum weight and finally integrated in the blimp structure. The kinematic principle is the same as that one of the cylindrical actuators. The geometric variables such as the length, the width and the position of the pivot line and number of layers were first systematically evaluated to find an optimal configuration. The internal stresses due to prestraining of the DE membranes were critical in respect to the stability of the active hinge in all the deflected positions. A stable configuration was found by positioning the pivot line at the most forward position directly at the control surface. The width and depth of the active hinge was chosen such that the resulting active strain in the membranes lead to a deflection angle of 30°. This was the case with a width of 10 mm and a depth of 50 mm. The required hinge moment was realized by stacking multiple layers on each side. In table 2 the resulting hinge moments at 30° deflection is shown as a function of the number of layers. Although for the required hinge moment of 1.5 N*cm two layers would have been necessary the active hinges realized for the EAP blimp were only with a single layer. This allowed a cruising speed of approx. 5 m/s, which was judged to be sufficient for indoor flying. The dynamic response of such active hinges is shown in Fig. 8. The figure shows the response of a single layer, double layer and triple layer active hinge when activated with U_{max} of 4 kV. From this figure it can be concluded, that approx. 75% of the total deflection is reached immediately after activation. The total deflection however is reached not earlier than approx. 5 seconds of activation. These results from the lab allowed concluding, that such active hinge actuators fulfil the requirements for the control surface actuators of our blimp.

In addition, several advantages result from the coverage of the gap between the control surfaces and the rudders by the planar actuators. These are a weight reduction, less friction, and a simpler construction, as the Bowden wires can be abandoned. This gap free rudder also leads to higher aerodynamic efficiency and less drag. This concept of an active hinge is not only interesting for airships, but also common airplanes could benefit from this development.

Table 2. Performance of active hinges: single layer, double layer and triple layer membranes.

Performance of active hinges

Number of layers	Hinge moment
1	0.76 N*cm
2	1.77 N*cm
3	2.76 N*cm

4. VERIFICATION OF SYSTEM PERFORMANCE

An ultimate load test with one quarter of the cross tail equipped with an active hinge was performed. The flutter characteristic was qualitatively explored in the range of 0 to 25 m/s wind speed. In general a very robust characteristic was found for the Depron ® made structure of the stabilizer and rudder part. However the EAP membranes of the active hinge showed some local fluttering when activated too much. This phenomenon is typical for such low stiff elements. The critical activation voltage is dependent on wind speed and rudder deflection angle. At an ultimate wind speed of 25 m/s the construction failed by large cyclic deflections of the stabilizer. The active hinge failed earlier by electrical breakdown due to this local fluttering of the membrane. Further experimental work is needed to quantitatively explore the boundaries of controllable structural and aerodynamic conditions.

Wind tunnel tests were performed in the larger subsonic wind tunnel of RUAG Aerospace in Emmen, Switzerland. The whole blimp was mounted at the gondola up-side-down on the 6 degree of freedom load cell of the wind tunnel. The volume was only partly filled with helium (rest with air), such that a small pretension was realized. The flow at low wind speeds of max 5 m/s was visualized and qualitatively assessed. The main goal of this test series was to evaluate wind tunnel testing methods for a quantitative characterization of such a blimp. Due to the soft fixation of the blimp in the wind tunnel the orientation of the blimp in the tunnel was dependent on the wind speed. This effect must be accounted for when such soft objects are tested in the wind tunnel. However first estimations of drag and lift coefficients were possible. The flow around the lifting body of the blimp, including the cross tail was primarily laminar within the envelope of the angle of attack and gear angle. Structural instabilities due to a low internal pressure were not seen.

Test flights were performed to estimate the turning performance, agility in vertical flight direction changes as well as acceleration and deceleration characteristics. In general a docile flight behavior was recognized, with good acceleration and deceleration performance. Turning agility and minimum turning radius was not yet optimal. In the next development step this weakness will further be optimized by changing shape, and position of the cross tail.

The first version of the blimp first flew on 21st of June in Berlin, and the second version, see Fig. 9 had his first flight on 8th of January in Duebendorf Switzerland and in both cases satisfactory flight control performances were demonstrated.

5. CONCLUSIONS AND FUTURE WORK

In this work two versions of a EAP blimp were designed, developed and produced, one with cylindrical actuators and one with novel membrane actuators driving rudders for flight control. With this project it could be shown, that these DE actuators have a good overall performance and that they fulfill systems requirements of a Lighter-than-Air vehicle. The 3.5 meter long blimp had in both versions a good flight performance. But the maneuverability can still be improved.

Based on these results future design studies at Empa are focusing the idea of a fish-like propulsion system. An undulatoric movement of the aft-body and a tail with an aero-elastic fin is proposed as the fish-like propulsion system. Since fish-like thrust generation mechanisms are well investigated in water surrounding, it is a legitimate question whether this mechanism is applicable to an airship in air. The adaptation of the locomotion mechanism in water to a deformable blimp in air is a matter of geometrical and fluid dynamical similarity that must be satisfied. With the theory of similarity it could be shown, that a 6 meter long, slowly cruising airship flapping his aft-body and tail fin is similar to a trout in water, if the dimensions of the body, including the fins and the deformation is geometrically equivalent.

The proposed radical new concept of a bionic airship is a multidisciplinary challenge. Many aspects, such as aerodynamics, aerostatics and structural mechanics have to be fulfilled in order to be a functional solution. For many of these design criteria the methods have not yet be developed in detail. However, if there is a combination of active envelope segments with a geometrical configuration a much more energy efficient, noiseless and environmental friendly transport system would be possible.

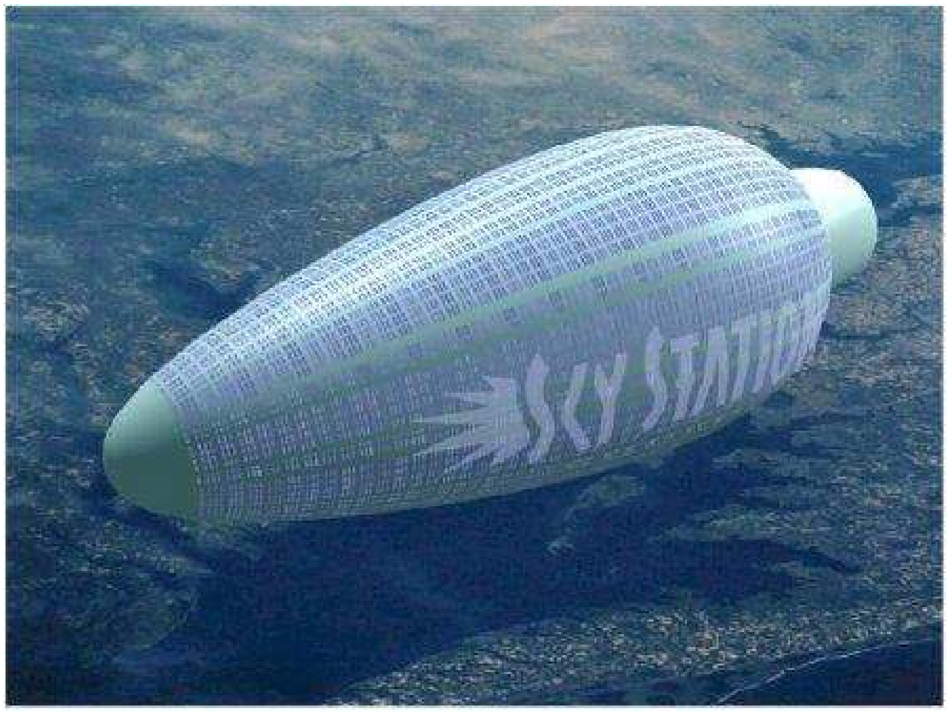

Fig. 1. Example of a Lighter-than-Air vehicle design as a stratospheric platform for telecommunication (sky station).

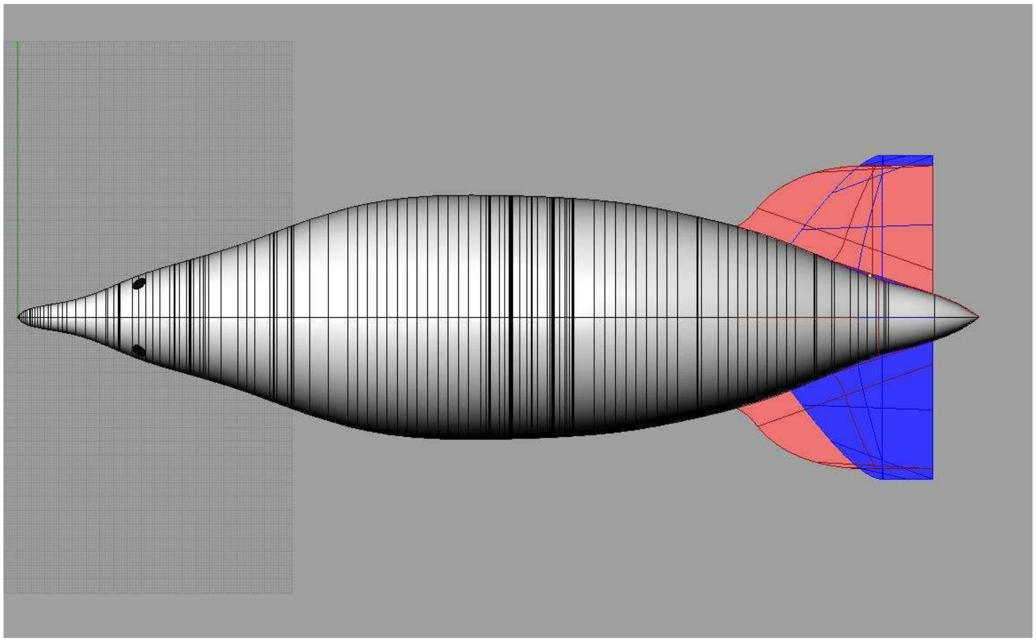

Fig. 2. Lifting body with the Penguin shape and two versions of the cross tail.

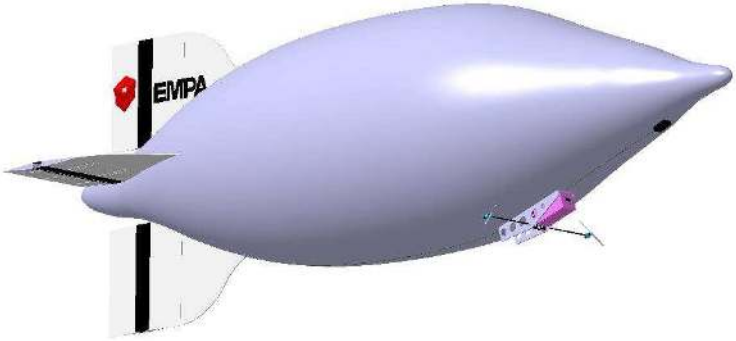

Fig. 3. Design of the EAP blimp showing the lifting body, the gondola with two propulsion motors and propellers and the cross tail (second version with active hinges).

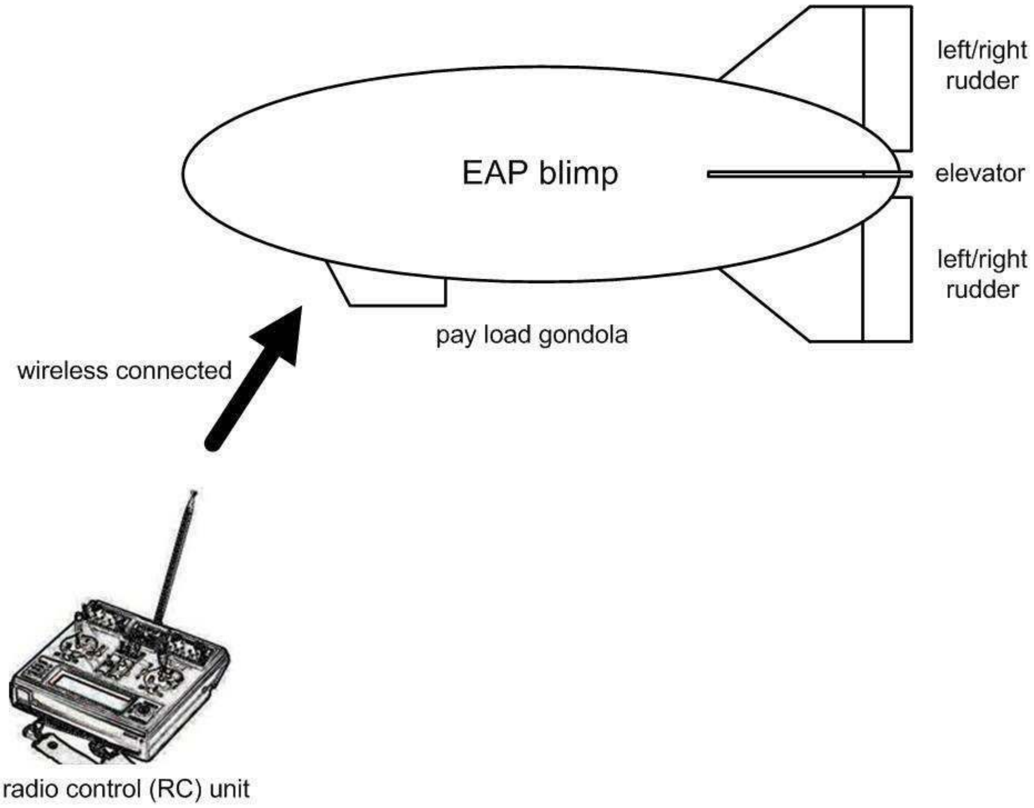

Fig. 4. Schematic representation of the EAP blimp system.

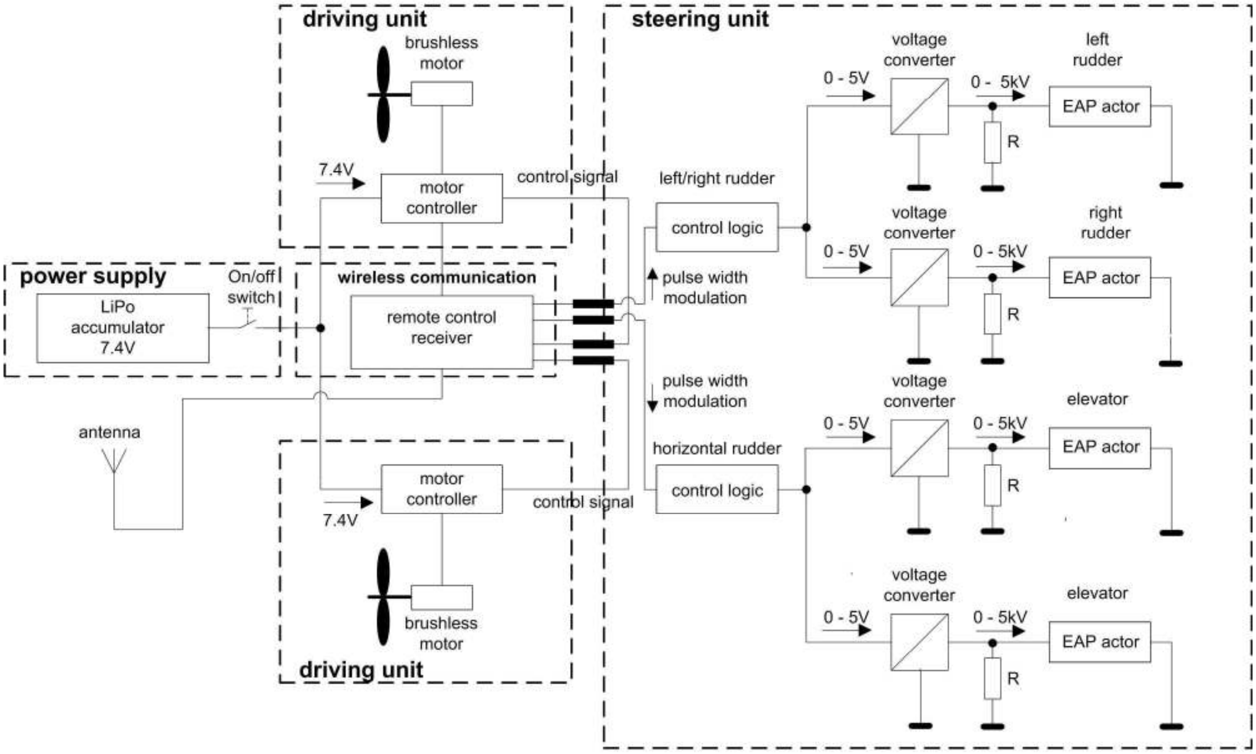

Fig. 5. Circuit diagram of the control device unit for the EAP blimp.

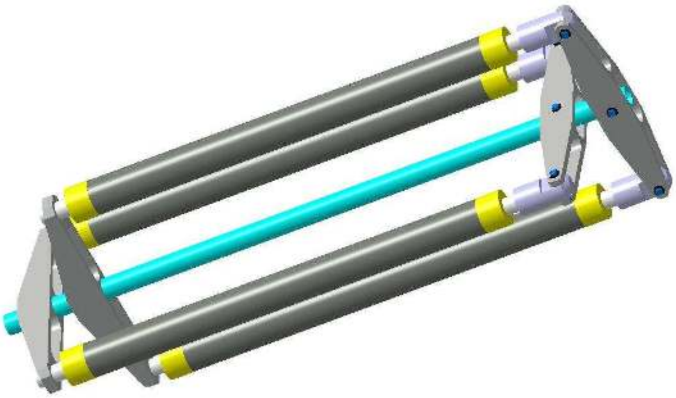

Fig. 6. Control surface actuators, first version: four cylindrial actuators two for vertical and horizontal rudder activation each.

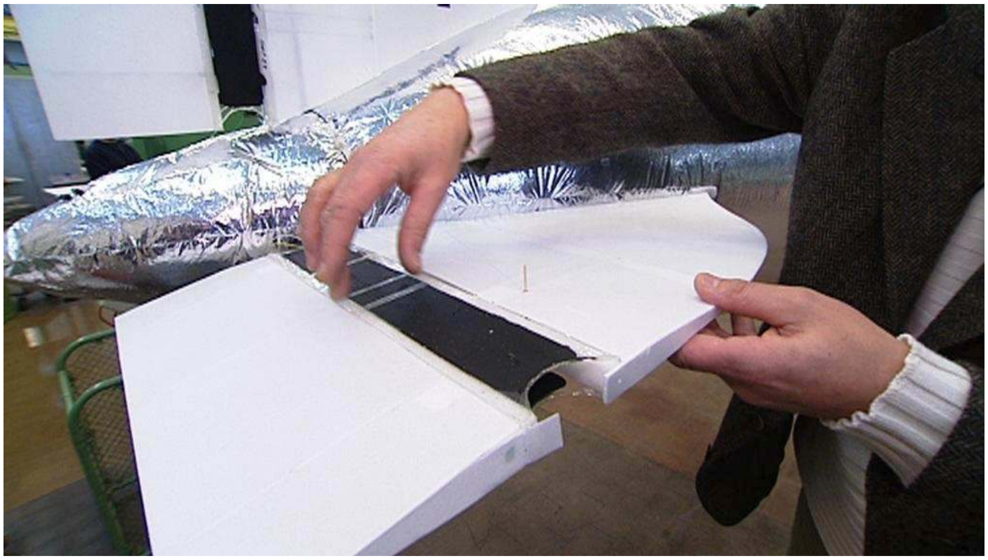

Fig. 7. Active hinge placed between the rudder (left) and the control surface (right) of the horizontal stabilizer.

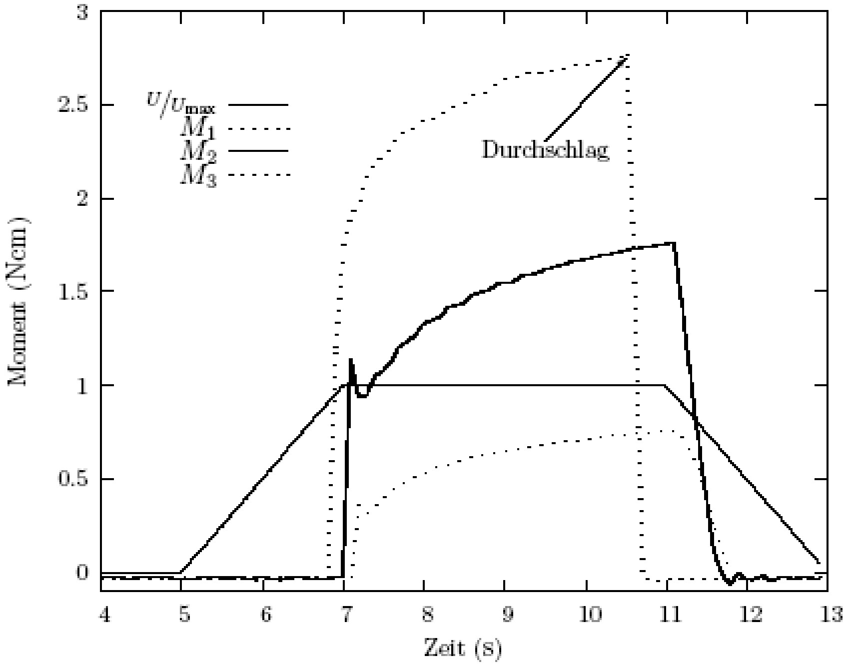

Fig. 8. Performance of active hinges: M_1 of single layer, M_2 for double layer and M_3 for triple layer membranes.

Fig. 9. Picture of the EAP blimp, with the second version of the cross tail: active hinges between the control surfaces and the rudders.

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