# Application of Electro-Active Materials to a Coaxial-Rotor NAV

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### ABSTRACT

**A new Nano Air Vehicle (NAV) configuration based on a coaxial nano rotor has been studied by ISAE. The coaxial rotor provides the thrust necessary for hovering and low speed translation flight. The major design challenge for rotary-wing NAVs is related to the difficulty of miniaturizing complex mechanisms such as a rotor cyclic pitch swashplate commonly used for controlling helicopters. The use of actuators made of smart materials is believed to allow for controlling rotary-wing NAVs in a much simpler and lighter way. The multidisciplinary subject of this complete system is separated into few parts. The studies of each subject are individually conducted before integrated in the future in order to optimize the global system. Those studies which are being carried out are shortly described in this paper.**

## 1 INTRODUCTION

Micro Air Vehicles (MAVs) appeared in 1997 as a response to a DARPA program. Numerous institutions and universities have focused research in that topic. Over the past ten years, MAVs developed by ISAE have included RC-controlled vehicles such as the *MinusKiool* and the *Plaster* and autonomous vehicles such as the *LadyBug*, the *TYTO* [1], the *Vision'Air*, and the *MAVion* [2-3]. Pure rotorcraft concepts have also been studied [3]. Following the interest expressed by DARPA in 2006, ISAE has started the development of Nano Aerial Vehicles (NAV) [4] in 2007 under the supervision of Prof. Moschetta. With reference to DARPA, NAV has a limitation of size about a half of MAV. NAV is expected to have a dimension of 7.5 cm (3 in.), a total mass of about 10 grams, including a payload of 2 grams. The NAV should have a VTOL capability (Vertical Taking-off and Landing), the ability of sustaining autonomous hover flight as well as low speed forward flight. Due to very limited size and weight, designing and constructing NAV seems very difficult to achieve on the sole basis of available commercial components provided by RC-model companies. Military as well as civil applications are envisioned for NAVs, including recognition missions in complex and confined environment such as flying into a collapsed building after an earthquake or releasing a payload in a very narrow space [5]. As a consequence, there are many problems to be studied including very low Reynolds number aerodynamic difficulty, new miniature and light material, sensor and components.

For a design of tiny air vehicle, there are generally three concepts widely used that are, fixed-wing, rotary-wing and flapping-wing. Fixed-wing configuration is normally applied for outdoor and high speed flight requirement due to its horizontal flight efficiency. However, fixed-wing configurations are not suitable for NAV missions which include hover flight. Rotary-wing and flapping-wing concepts have been analyzed and compared by Liu [6], who concludes that the hovering efficiency of both concepts is comparable. Because flapping-wing mechanisms are more difficult to fabricate and control, a rotary-wing configuration has been selected, based on a NAno Coaxial Rotor (*NACR*). Coaxial Rotary wing concepts have been widely used because they intrinsically sustain hover flight without resorting to anti-torque rotors [7]. A compromise control method and vehicle configuration has to be adopted to achieve the objective of precise flight stability and satisfy the weight limitation of *NACR*.


(a) Coaxial Rotor NAV concept (b) Quad-rotor Indoor Flying RC

(c) Fixed Wing NAV, U. of Florida

(d) Prox dynamics's miniature flying machine

Figure 1: Present of Configuration used in Small UAVs.

The major design challenge for rotary-wing NAVs is related to the multidisciplinary design and the difficulty of miniaturizing complex mechanisms such as a rotor cyclic pitch swashplate commonly used for controlling helicopters. The use of actuators made of smart materials is believed to allow for controlling rotary-wing NAVs in a much simpler and lighter way.

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This paper introduces and summarizes the present and coming future state of the *NACR* project. The concept and design overview will be discussed, followed by the study of each part of project. The test set up of smart actuator and test bench of propulsive characteristics will be presented. The fabrication method for the tiny structure or body of *NACR* will also be addressed.

## 2 DESIGN OVERVIEW

There are different solutions to control micro and nano aerial vehicle such as adding control surfaces just downstream the rotor or propeller as successfully demonstrated by *MAVion* [8], *MiniVertiGo* [9] and *Vision'Air*. Control alternatives include using additional propulsive or force generator system (ie, tail rotor) [10], center of gravity shifting [11], and tilting one or two rotors. Furthermore, an advanced concept using smart material may be considered such as a) smart active control intelligent rotor blade instead of changing cyclic pitch by swashplate, b) smart muscle structure. Applying surface control looks convenient for design but has drawback of additional drag and download force reducing flight autonomy. Using auxiliary force generator involves additional mass and may also increase the vehicle size. Based on present available technology, using smart material as an intelligent blade and a smart muscle structure is not feasible in the near future. Controlling the CG position has been implemented on micro air vehicle as reported in Ref. 11. However, this concept does not seem to be appropriate for the NAV size. Change CG position may be done by adjust the position of battery, but moment created is very small according to the small mass of battery represented in an estimated weight balance distribution (see Figure 5). After comparison, the control method of tilt rotor is selected in this *NACR* project, relying on the fast development of intelligent and light actuators over the past few years.

### *First Concept and Bench Model*

The estimated maximum required thrust, normal force and tilt angle of upper rotor to reach 2m/s translation movement are 0.15N, 0.03N, and 10degrees, respectively. Based on these estimations, several light-weight actuators are commercially available. Table 1 summarizes some characteristics of miniature servos and actuators commercially available.

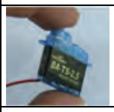
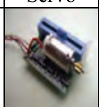
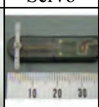
| Commercial Actuator | Blue Arrow | Linear Servo | Smart Servo | Magnetic Actuator1 | Magnetic Actuator2 |
|---|---|---|---|---|---|
| |  |  |  |  |  |
| Mass (g) | 2.8 | 2 | 1 | 0.4 | 0.75 |
| Size (mm) | 19x20x8 | 21x13x 9 | 38x9x3 | 7x8x4 | 9x10x8 |
| Torque (g.cm) | 150 | 160g force | 15 | 0.4 | 0.8 |
| Max. Motion | 80deg | 14mm | 30deg | 4mm | 5.5mm |
| Time (sec) | 0.22 (60deg) | 0.15 (full) | - | - | - |
| Current (mA) | 100 | 100 | 80 | 45 | 42 |

Table 1: Miniature servos commercially available.

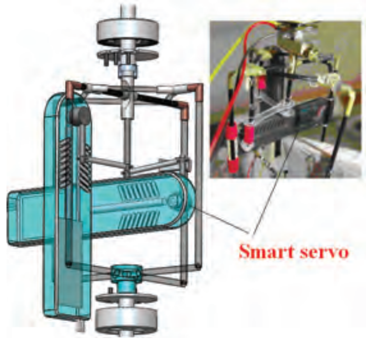



Figure 2: 1st NACR Bench Model.

Magnetic actuator is one choice because of its lighter weight of 0.4g. Considering its smaller torque, another bio-wire smart servo actuator, mass of 1g, was used in the first *NACR* bench model (see Fig.2), two smart servos are used to tilt the upper rotor for pitch and roll control. The structure is made of 1mm-carbon rods connected by a metal tube connector and just glued together. The total mass of that bench model is around 20 grams. A pair of rotors designed by Liu [12] has been installed. Measurement of total thrust performance is performed by new low friction magnetic test bench "Pop-Eye" shown in Figure 3. Yet, only thrust is measured, side force and pitching moment which are the most interesting parameters for the tilt-concept could be measured with that test bench.

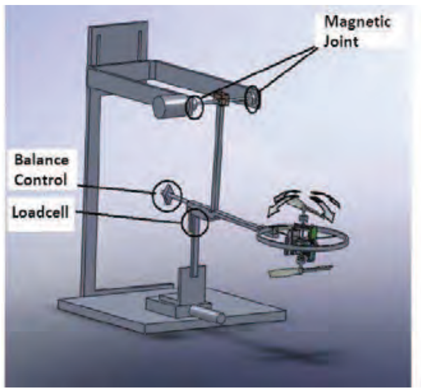



Figure 3: Pop-Eye Test Bench.

### *Current NACR Concept*

Considering fast and precise stability requirement, new actuators with shorter response time, lighter weight and lower power consumption are required to replace such a complex configuration based on 2 SmartServos. EAPs (Electro-Active Polymers) with fast reaction speed (up to µsec) on one side and low density with great resilience on the other side, compare favorably with SMA (Shape Memory Alloys) and EAC (Electro-Active Ceramics) [13] respectively. Among them IPMC (Ionic Polymer-Metal Composites) requiring only low drive voltages may be seen compatible with extremely uncluttered NAV power supply (reduced to one cell of 3.7V Lithium-Battery for the *NACR*). In addition, IPMC combine advantages towards miniaturization, light weight with large displacements and endurance. As an emerging technology, IPMC concentrate intensive research effort and still promises versatility in mechanical properties through the control of a wide range of parameters such as ions and solvent nature, membrane thickness etc... IPMC have already been designed for actuators in flapping devices [14].

The relative limitations of IMPC low energy density and actuation force may be overcome from the overall mechanism design. To minimize the complexity of 2-DoF tilt rotor, only 1-DoF tilt rotor is first investigated in the present work. A pitch motion can be obtained by tilting the upper rotor while yaw motion can be achieved by controlling the rotation speeds of the two counter-rotating rotors. Primary configurations to control tilt-angle of upper rotor of *NACR* with IPMC actuators are illustrated in Fig.4. In Fig. 4-left, IPMC actuator belongs to the *NACR* mechanical structure, acting as a muscle, the upper rotor is directly supported by two parallel IPMCs. Axial, normal and torsion forces act on the IPMCs in that configuration. Another configuration is considered in Fig. 4-right, where the IPMC is only used to control the tilt-angle. In a further perspective, IPMC may also be considered in the building of smart/intelligent rotor blades as well. The expected total mass of *NACR* including 2g-payload is about 17g. It is noticeable that mass of propulsion system (battery, 2-motors, 2-rotors, and 2-speed controls) and mass of electronics parts are about one-third of total weight (6.5 and 6g, respectively).

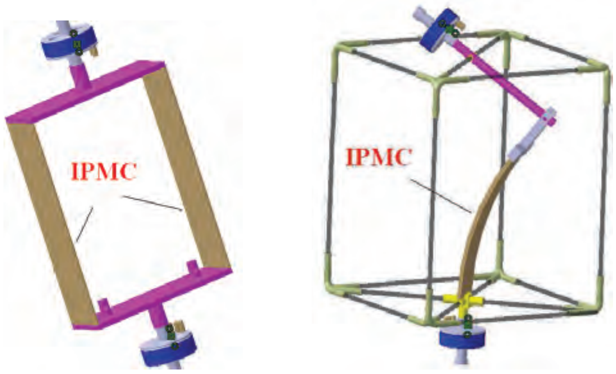



Figure 4: NACR Concept using Smart Actuator.
Left: Smart Muscle concept which upper rotor is support by IPMC,
Right: Tilt-rotor configuration controlled by smart IPMC actuator

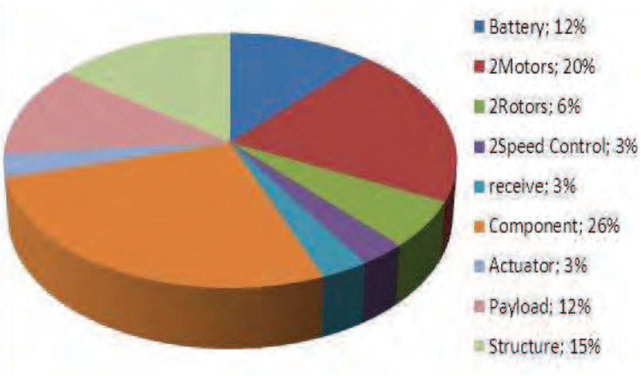
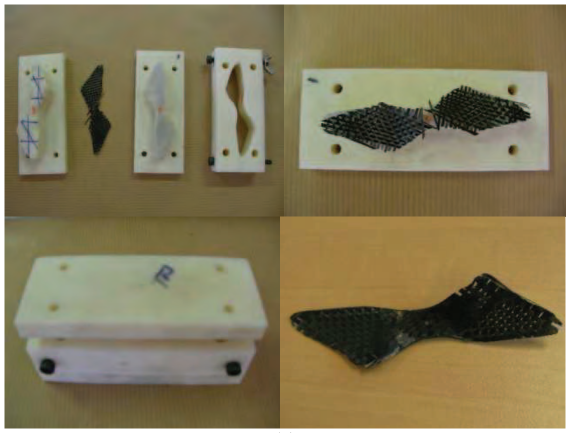



Figure 5: Expected mass distribution of NACR (total mass = 17 g)

## 3 PROPELLER DESIGN AND FABRICATION

Design of nano coaxial rotor is based on the optimization of hovering. Effect and interaction of each rotor to another rotor are taken into account in the optimized design preliminary calculated by XROTOR code of MIT. Induced velocity of the 1st rotor is inserted into the calculation of the 2nd rotor till the calculation converges [12]. Navier-Stokes numerical results are then compared using several turbulence models. Nano coaxial rotors are shown in Fig. 6.

Figure 6: Nano Coaxial Rotor designed by Liu



(a)

(b)

Figure 7: Fabrication Process of Nano Coaxial Rotor.

The rotor is then made. Its small dimension makes them difficult to fabricate. Accuracy in fabrication is critical and can affect the rotor performance. The blade thickness must be minimized to obtain the best performances while a thin section is convenient for the fabrication by composite material.

The 2-side molds are fabricated by a 3D printer. The first try, rotors are made using wet layup; 100g/m$^2$ carbon tissue (the thinness carbon tissue we have) and epoxy. The form of rotor is first cut by hand before layout on the molds. However the extremity is run out as showed in Figure 7(a). Then it was compressed by another mold. After drying for 15 hours, the edge of propeller has not good shape as desired. In an attempt to improve the shortcomings of carbon prototype, 42g/m$^2$ fiber glass is used. The fabrication processes are detailed in Figure 7(b). This time, tissue of fiber glass is layout on the molds without cutting the shape. Several layers of tissue are tried to get difference flexibility. The last layer is covered by peel piles in order to obtain smooth surface and also to absorb the exceed epoxy. After 15 hours, the shape of rotor is trimmed by cutter and sanded before being released from the molds.

## 4 AERODYNAMIC AND PROPULSION

To find precise flight dynamic modeling, thrust and torque of each rotor should clearly identified. Because of its very miniature size, characterizations of their aerodynamic and propulsive performance are challenging. The numerical simulation of very low blade-Reynolds number aerodynamics is strenuous. Experimental measurement of such a low force-moment is also very difficult. In the present project, the objective is to find an influence and interaction of each rotor on another rotor especially when the upper rotor is tilted. A normal force on the lower rotor is expected. Both numerical simulation and experimental test are performed and will be compared in the future.

### *Numerical Simulation*

In this study, the overset structured meshes are used. Different from the meshes for MRF model, five isolated blocks in which four blocks conform four blades and a cylindrical block for background mesh are generated. Several rotor pitching cases are studied by Liu [12] such illustrated in Figure 8.

### *Test Bench for NACR Concept*

The challenge of experiment of nano rotor is to measure precisely small thrust, torque and other parameters. As the expected maximum thrust of each rotor is order of 10 grams, sensor should have accuracy better than 0.5 grams force to achieve an error of less than 5%. Many single-rotor test benches had been developed and tested at ISAE since 2008 [18]. The study is satisfied but all of them are only two components (thrust and torque). ISAE developed new high precision 5-component nano sting balance in 2009. Thrust and torque of coaxial nano rotor were observed by this high precision nano sting balance but they are just measured together [12]. Now *NACR* is more and more challenging since the objective is to measure very petite influence of tilt-angle of the rotor in particular on the lower rotor. Rotor must be separately identified.

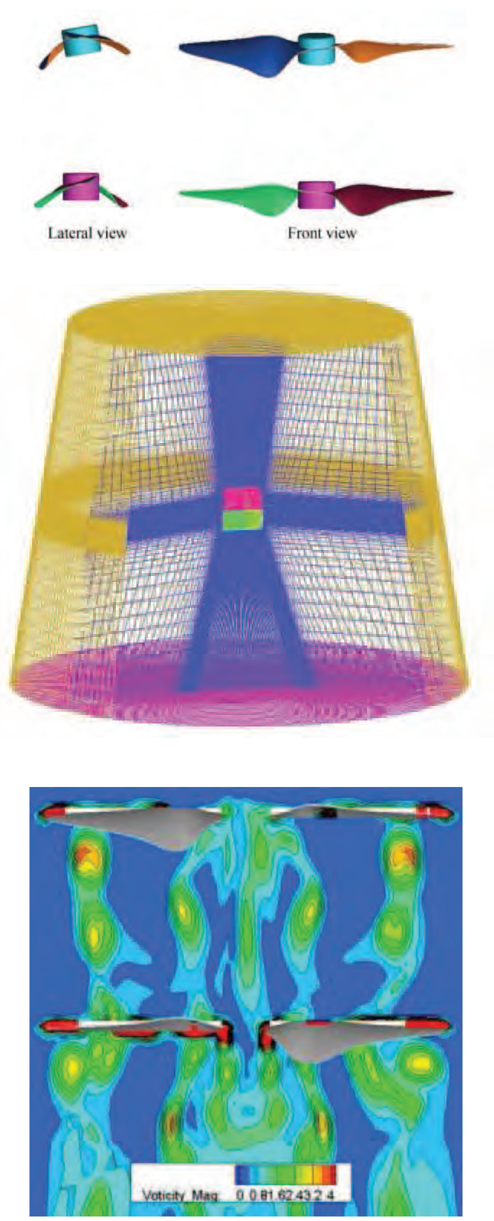



Figure 8: Numerical Simulation of Coaxial Nano Rotor done by Liu.

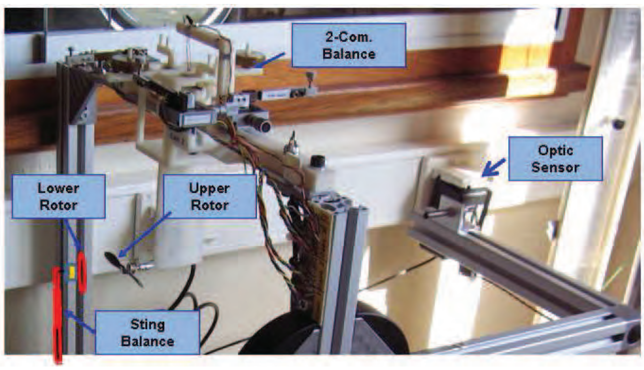



Figure 8: Experimental Set up of Tilt-Rotor in *NACR* project.

To successfully investigate the rotors, all forces and moments should be observed. Therefore, they have to be identified by the 5-component balance. Yet, only one 5-component balance is available. New solution should be found. Following the fact that blowing induced flow of the upper rotor is strongly faster than suction induced flow of the lower rotor, the presumption is applied. The upper rotor gives only thrust aligned to the motor axis while the lower rotor may produce other lateral forces / moments. Thus, a new experimental test set up is installed. The upper rotor is mounted by the nano bench and the lower rotor is carefully supported by 5-component nano sting balance as illustrated in Figure 8. Both balances are installed together. The mechanical set up allows for adjustable distance and tilt-angle. So normal forces, side force, pitch and yaw moment of lower rotor can be measured beside thrust/torque of both rotors. All electric parameters and rotor speeds will be measured as well.

## 5 STRUCTURE

Main function of structure for *NACR* is holding and connecting motors and all other components. Nevertheless, since the components selected for *NACR* must be very light, they are usually fragile. Then, it is great to well protect them. Therefore, the structure of *NACR* is designed to hold and cover all other components. The light and stiff material must be carefully selected. On shelf carbon rod is often used for the structure of MAVs such as seen by *Vision'Air* and *Link MAV* in Figure 9. This material has already proved its stiffness.

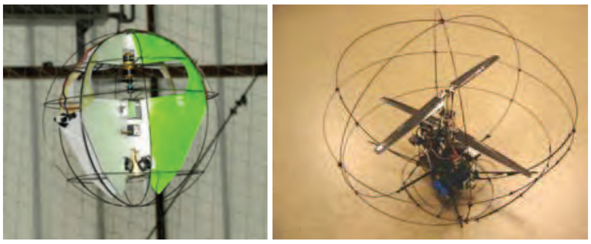


Figure 9: MAV.
Left: 1st version of *Vision'Air* of ISAE (2007)
Right: *Link MAV* of Linkoping University (IMAV07, Toulouse)

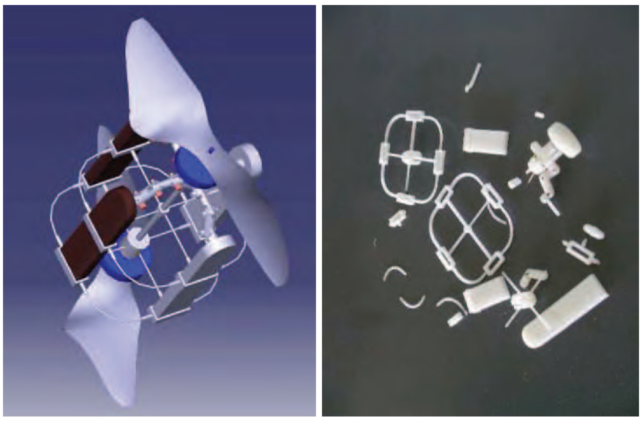


Figure 10: First Attempt of Structure Design.

However, it is not easy to find the right and optimized dimension of carbon rod because the diameter of vehicle is very small (around 8 cm). Off-the-shelves 0.5mm carbon rods cannot be shaped to a circle form, while that of 0.3mm is too small and soft. In addition, it is not easy to make the connection between each part by on-shelf carbon rod.

Due to the structure of *NACR* which has many connections, fabrication by rapid prototype machine has been carried out. The structure was designed by CATIA (Figure 10-left), and sent to a CNC machine. The outcome is presented in Figure 10-right. However, the structure is very fragile since the machine follows Cartesian path lines.

Figure 11: Uni-Direction Carbon In-House NAV Structure Solution.

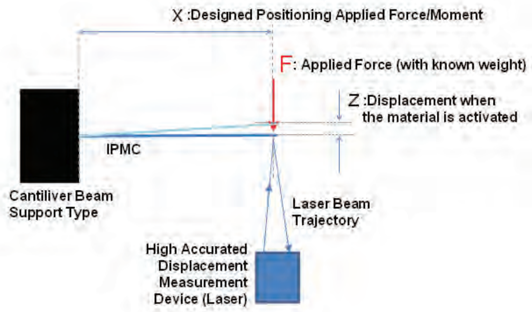
Finally, carbon material has been re-considered. Uni-direction carbon and epoxy is used for a wet layup. In the first attempt, the wet-carbon is formed by a simple cylindrical tube. As illustrated in Figure 11, a spiral structure is tried with the expectation of flexibility between two rotors. The weight of this first attempt is about 2.5g.

## 6 SMART ACTUATORS TEST

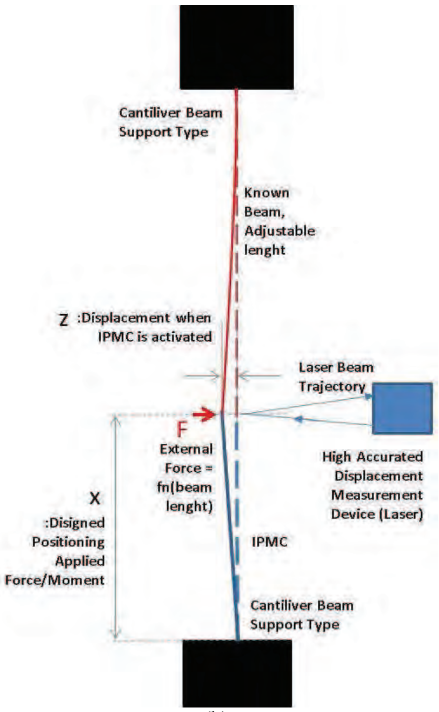
Experimental test is conducted to characterize the performance and efficiency of new smart actuators. As a strat, simple and basic tests were performed as shown in Fig. 12(a). The accurate tip displacement under several external constant forces was measured by a high resolution laser device with the accuracy of 1cm per volt. Mechanical property of this IPMC can be analyzed. The experimental setup with micro balance measurement system [19] according to the reference is then proposed to be used for force testing of IPMC samples. Proper specifications for IMPC design according to NAV requirements are extracted. The IPMC tested in this study has a size of 40x10x0.3mm and a mass of 0.4g.

As the application of IPMC when installed to the prototype is not simple in the first test, the following work will be to test IPMCs under the generic environment test bench. The assumption is made that when the tilt-angle is increased, flight speed and normal force on rotor increase. Therefore, the constant external load measurement in the previous set up is not exactly true. New set up is represented in Figure 12(b). Known-property miniature beam is utilized to simulate the external force which is a function of tilt-angle and length of beam.

The numerical models of different structures are being set up in view to establish proper control loops to achieve the objective of precision control of IPMC actuator, which is a critical process for NAVs flight stability.




(a)
Figure 12: IPMC Characterization Test Bench.



(b)

Figure 12: IPMC Characterization Test Bench (cont.)

## 7 Electronic components

This is another very important topic of *NACR*. Normally, electronic of flying rotary-wing RC consists of a receiver, speed controller, gyroscope, servos or actuators and the lightest mass of each component that can be found commercially are 0.3, 0.2, 2.3, 0.4g, respectively. *NACR* requires a pair of rotors and a minimum of one actuator so the total mass of electronic components is equal to 5.7g. Moreover, to achieve autonomous, controller and other sensor are required on board. Therefore it is not possible to use on-shelf components as electronics part of *NACR*. Small and miniature air vehicle needs special component multidisciplinary optimized design such as shape and structure to be as light as possible. All electronic components, such as speed control, sensors, actuator, and etc., may be integrated on board. PCB board of electronic can be a part of structure as well. The design of electronic components is being cooperated with other department of ISAE. The objective is to reach 5grams of electronic board including sensors.

## 8 Conclusion

A new concept of coaxial rotor Nano Air Vehicle (NAV) has been presented in this paper. The upper rotor can be tilted in order to provide roll and pitch control while differential throttle provides control in yaw. Among several electro-active actuators, IPMC has been selected because of the low driving voltage and the reasonable amplitude provided. Before designing a flying prototype, IPMC actuators need to be tested and compared with existing actuators. The propeller interaction will be studied using a new test bench devoted to extremely low thrust force as produced by a coaxial nano rotor. In the near future, a tilt-rotor concept will be evaluated by scaling up the platform. The prototype by a factor of 2, called MIcro Coaxial COunter-rotating Rotors (*MICCOR*), will be made at Kasetsart University. A radio-controlled prototype will be equipped with three gyroscopes.

## Acknowledgment

Authors would like to thank for the financial funding of STAE (French Scientific and Technology for Aeronautic and Space Foundation) and EMMAV project. Without help and support of several colleges from different department at ISAE, the project could not be conducted. The first authors would like to thank also to Kasetsart University for the partial support of his visiting at ISAE during summer period.

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