

Passively stable rotor system for indoor hovering UAS

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ABSTRACT

Small rotary wing air vehicles and in particular those intended for indoor use can benefit hugely from utilizing a rotor system that enables passively stable flight including stable hover. This paper describes the inherently stable Proxflyer [1] rotor system and gives examples of possible applications.

1. INTRODUCTION

Just a few years ago most people considered passively stable hover to be impossible - helicopters were unstable and required either a sophisticated gyro system or a skilled pilot to hover. One of the first completely passively stable rotor systems to be developed was the Proxflyer system. This coaxial rotor system enables a small rotary wing air vehicle to hover and maneuver around a room without any gyros, servos or other form of advanced control system. Details on how the system works and why it is passively stable are discussed. The main limitation to the system, its inability to operate outdoors and under windy conditions will also be commented.

The Proxflyer rotors has been used in indoor toy helicopters for the past few years, however, now the system is developed further and offers new possibilities to the science community in the form of flying platforms e.g. for swarming robot science and stereo vision projects.

Because an air vehicle equipped with a passively stable rotor system does not require onboard sensors and computing power to stabilize it, the vehicle can carry more weight than alternative solutions. The system also saves time during the project's execution as keeping the aircraft stable no longer has to be part of any primary tasks. The rotors operate at relatively low RPM compared to

conventional rotors and is therefore both efficient and safe. Due to its simplicity, the Proxflyer rotor system can be realized at a relatively low cost.

2. BACKGROUND

Petter Muren, Prox Dynamics AS, has more than 30 years experience in designing and building remote controlled airplanes and helicopters. In 1990 he started the development of a series of different electric powered helicopters. These, mostly tandem and co-axial type helicopters, were large models and they were far from being passively stable. Several of them barely made it into the air. The battery technology at that time did not allow for long flights, hence, most of the early models got electric power via a tether from the ground.

The work on the Proxflyer helicopters started about 8 years ago. These early models challenged the "known" facts about the stability of helicopters and they were based on previous co-axial rotor models. It has always been a target to have as stable helicopters as possible, but at the same time a commercial helicopter need to handle wind, turbulence and have as high forward speed as possible. Because of this there has not been considered practical to try to stabilize a helicopter solely with respect to the surrounding air.

Battery technology and constantly smaller control electronics have finally made micro indoor flying platforms a real possibility. The main difference between indoor and outdoor environment is the lack of wind and turbulence.

Maybe the "impossible" passively stable helicopter could be realized by approaching the stability problem in a completely different way. What if it was possible to achieve hovering flight that was

completely stable with respect to the surrounding air? Would it be possible to design a helicopter that interacted with the air in which it was flying in such a way that it passively remained fixed in one position in space?

The development of the Proxflyer helicopters proved that this was indeed possible, when in 2002, passively stable hover were achieved for the first time. Since then several other stable rotor systems, mostly for use in indoor toy helicopters, have been developed.

3. THE PROXFLYER CONCEPT

The rotor [2] used in these passively stable aircrafts have a generally fixed geometry and they are tiltably connected to their rotor shaft. In Fig.1 the orthogonally oriented hinge axis (47,49) are shown. However, the inner part of the rotor blades have a pitch angle (41) that is fixed relative to a reference plane (B) perpendicular to the rotor shaft, whereas the outer part of the rotor blades have a pitch angle (42) that is fixed relative to the rotational plane (A) of the rotor. The fixed pitch in the outer part comes from the tip of the rotor blades being fixed to a ring. This ring by definition lies in the rotational plane (A) of the rotor.

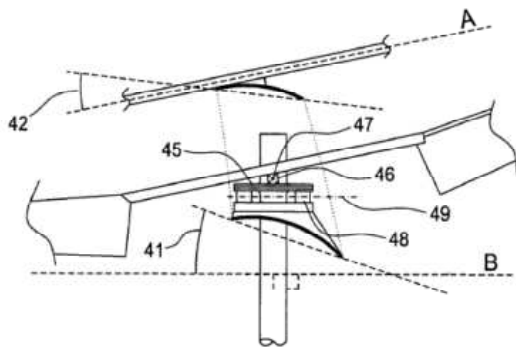


Fig.1 Pitch angles and hinge axis in a tilted rotor [2].

The fixed pitch angle in the inner part of the blades together with the blades being connected to the ring would seem to imply a rigid rotor. However, because the very thin and curved rotor blades can twist along their centerline, the rotors are in fact more or less free floating with respect to the helicopter. The rotor can easily tilt in any direction. If the rotating plane is tilted, each rotor blade will go through a cycle of tilting (move up and down) and twisting as the rotor spins.

Together with the co-axial design, the free floating rotors eliminate unwanted gyroscopic forces between the rotors and the helicopter.

At the same time, due mainly to aerodynamic forces, the rotors will follow any tilting of the rotor shaft, thus allowing the helicopter to be maneuvered by just gently tilting it in the desired direction of flight. This is achieved because the inner parts of the rotor blades have a fixed pitch angle (41) with respect to the reference plane (B) perpendicular to the shaft. If the rotor has been tilted and the blades follow a tilted path with respect to the reference plane, the rotor blades will move up and down as they rotate and the inner part of the blades will actually have different angles of attack in different parts of the rotation. This again, gives different lift in the different parts of the rotation, thereby tilting the rotor back perpendicular to the shaft. In other words; stabilizing the rotors with respect to the rotor shaft. This also secures that the rotors follow any tilting of the helicopter.

Because the outer part of the rotor blades have a pitch angle (42) fixed relative to the rotational plane (A) or the ring, the rotors have a high tendency to back-flap or tilt up in front due to horizontal movements. This high tilting tendency is the opposite of normal desired rotor behavior and ensures that even small movements with respect to the surrounding air, will tilt the rotors and try to stop or slow down the horizontal movement of the helicopter. This is also more or less the opposite action of what the inner part of the rotor blades does, and these two functions may be tuned against each other to achieve more or less stability.

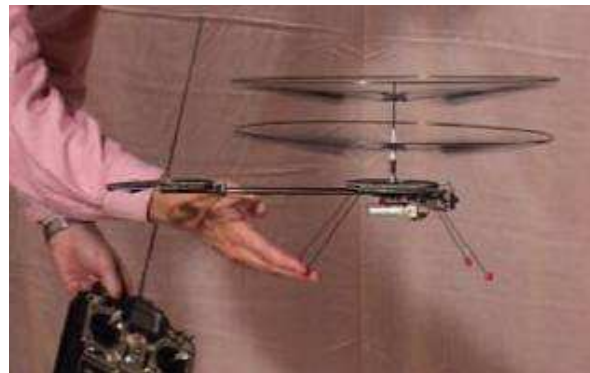


Fig.2 The passively stable Proxflyer Mosquito helicopter.

The concept in its original configuration allows for moderate forward speeds and operations under no-wind conditions and it provides absolutely stable hover without use of any electronic control systems.

The rotors operate at very low RPM and together with the co-axial design and up to 8 rotor blades the efficiency of this helicopter is very good. With the latest in battery technology the 120 grams Mosquito could easily fly for almost 1 hour. The low RPM

together with the gear system using rubber bands and pulleys enables absolutely silent operation. The pulley system, however, have proven to be a little less efficient compared to a one-stage gear.

3.1. Main benefits

The main benefits are:

- Passively stable, hover and forward flight
- Simple electronics, no servos or actuators
- Relative simple mechanics
- High efficiency, long flight times
- Very easy to pilot and command
- Generally low noise level

3.2. Possible disadvantages

Possible disadvantages are:

- Low forward speed
- Not possible to operate in wind (outdoors)
- Relative sensitive to C.G. position

For autonomous control it has been found that a yaw rate or head holding gyro might prove necessary due to the fact the each of the two contra-rotating rotors are driven by separate electric motors. The motors, unless they are RPM controlled, have a tendency to run a little different due to e.g. temperature changes. This of course influences on the yaw stability.

3.3. Control principles

The control is very easy [1], [2]:

- Vertically the helicopter is controlled by the speed of the two main rotors.
- Yaw control, turning the helicopter from side to side, is achieved by increasing the speed of one rotor and reducing the speed of the other rotor by the same amount.
- Horizontally the helicopter is controlled in forward and aft direction. To enter into forward flight the helicopter is tilted by a small horizontally orientated propeller positioned at the back of the helicopter. The main rotors follow the tilting of the rotor shaft and pull the helicopter forward.
- To go sideways you first have to turn the helicopter in the direction you want to go and then fly forward in that direction.

The control of this helicopter is not very different from what you do when you control a RC car, the only addition being the vertical motion.

If for some reason you loose control, you simply let go of the control stick and the helicopter will enter into stable hover by itself.

4. DIFFERENT APPLICATIONS FOR THE PASSIVELY STABLE ROTOR SYSTEM

There are many applications that benefit from utilizing an inherently passively stable rotor system.

4.1. Stable platform for wireless camera



Fig.3 The Proxflyer Mosquito equipped with a wireless video camera is controlled solely by looking at a large video conferencing screen displaying the pictures coming from the helicopter.

The 120 grams VTOL Micro UAV Mosquito utilizing this co-axial rotor system has been used in several appearances and demonstrations. With its onboard 2.4 GHz wireless video camera, it has been used to e.g. film an audience while flying overhead inside a conference room. The pictures have been recorded or displayed on monitors.

In August 2003 this helicopter performed what is believed to be the first ever controlled flight where the pilot operated the helicopter via conferencing from a remote position by looking at a large video screen displaying the pictures from the helicopter. The pictures were transmitted to the remote location by a Tandberg video conferencing system using ISDN telephone lines. The stable helicopter performed two successful flights of approximately 1 minute. Each flight included: Take off, forward flights, turns and a controlled landing. During one of the flights, the pilot at the remote end, purely by observing the pictures coming from the helicopter were able to discover and recognize a person coming into the room where the flight took place. The helicopter was controlled by a normal RC transmitter capable of sending control signals to the remote located helicopter. No gyros or any kind of positioning system were used.

4.2. Micro and Nano sized helicopters

The Proxflyer helicopters have no need for servos or other control systems; hence, it is possible to build

very small and lightweight sub-micro helicopters or Nano Air Vehicles.

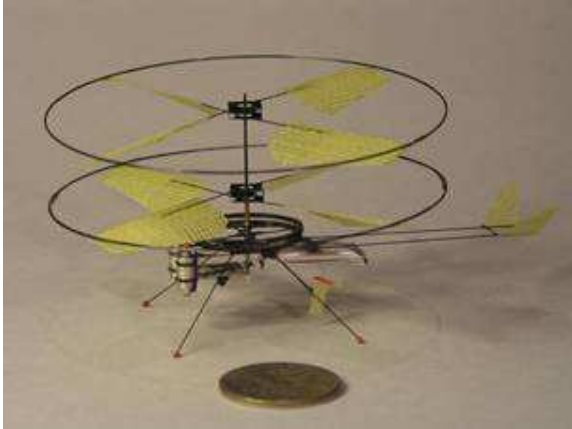


Fig.4 The 3.0 grams Nanoflyer from 2004

The Nanoflyer [1] was presented in September 2004. At that time this was by far the smallest helicopter presented to the public. It has a rotor diameter of 85 mm, two 4 mm electric motors and a 30 mAh lithium polymer battery. It is controlled by a short range 2 channel IR link with onboard mixing and high frequency electronic speed controllers. The Nanoflyer has a flight time of about 10 minute and the total weight is 3.0 grams - about the weight of half a sheet of paper.

An even smaller version, the Picoflyer with a rotor diameter of only 60 mm and 3 ch control was referred to as a proof of concept when DARPA started their Nano Air Vehicle program in 2005.

4.3. Toy helicopters

Because a helicopter utilizing the Proxflyer rotor system is passively stable it is also extremely easy to control. It is actually so easy to fly that a child without any experience from helicopters or model airplanes is capable of flying it, even the first time he or she try it.

This unique simplicity led to the development of the Bladerunner toy helicopter. This helicopter was the first passively stable toy helicopter for indoor use.

The Bladerunner was introduced before Christmas 2004 and sold in over 100.000 samples within a few weeks. This toy helicopter had a weight of 50 grams, a rotor diameter of 290 mm and a normal flight time of 5 – 8 minutes. Since the start of the indoor toy helicopter boom, the original Bladerunner and later versions like the Micro Mosquito [3] have sold in over 2 million samples. In addition we have seen

huge numbers of copies and knock-off helicopters bringing the estimated number of helicopters using the Proxflyer rotor system to over 5 millions.

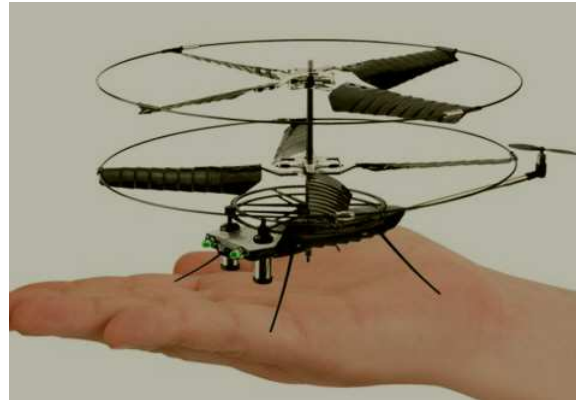


Fig.5 Micro Mosquito, 25 grams RC toy helicopter utilizing the Proxflyer rotor system [3].

Possible one of the most interesting aspects of these toy helicopters are the low production cost. The reason for this low cost is the simple concept and design, high production volume and also the fact that they are all produced in China. The normal retail price is well below US\$ 100, sometimes as low as US\$ 40 with everything included (ready to fly helicopter, remote control unit and battery charger).

4.4. Universities

About 15 of the Mosquito helicopter seen in Fig.2 have been used in science labs and at Universities around the world. Most of these helicopters are used to study autonomous operation of flying platforms.

Passively stable helicopters are also used in Owen Holland's UltraSwarm project at the University of Essex. This project is exploring ways of getting a group of aircrafts to fly like a flock of birds. At the same time the swarm will perform task-related computation across a distributed wireless network.

The swarm project first used rebuilt Bladerunner helicopters fitted with a miniature Linux computer, a small video camera and a Bluetooth module to communicate with the ground control and other vehicles. When the flock has been completed, the Bluetooth modules will be configured as a single pico-net with the master on the ground control computer system. Like the prototype, each helicopter will also carry a color video camera that will be used both for flight control, and for gathering data for a cooperative visual task. The Swarm project is continued through the new SwarMAV initiative at the University of Essex [4].

4.5. Government use

Apart from being presented at several international conferences sponsored by both US and European military services a special MAV version has been developed for a military science lab.

The Proxflyer MAV was developed for the US Army research center at Redstone Arsenal, Alabama, to study stereo-vision operations [5].



Fig.6 The Proxflyer MAV developed for the US Army to study stereo-vision operations.

The helicopter was intended for indoor operations and had the following specifications:

Rotor diameters:	320 mm
Max length:	430 mm
Height:	180 mm
Weight incl. cameras:	210 grams
Flight time:	10 minutes
Battery (li-po):	7.2V, 1400mAh
Control:	4 ch RC system
Frequency:	35.06 MHz
Yaw control:	Head-holding gyro
Cameras:	2 forward looking
Frame rate:	60 Hz interlaced
Video transmitters:	2 x 2.4 GHz



Fig.7 Details of the wireless stereo vision cameras.

5. PD-250L, PASSIVELY STABLE INDOOR HOVERING UAS

The passively stable Proxflyer type helicopters used by universities and labs have some limitations that create different challenges to the engineers and scientists. To increase lifting capacity, extend operation time (flying time) and enable control in all directions (added roll control) a new helicopter has been developed [6].

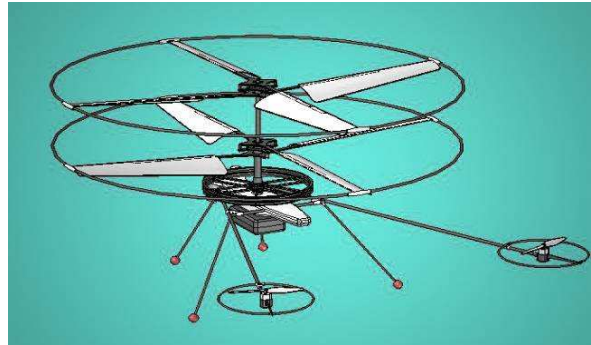


Fig.8 Early drawing of the PD-250L flying science platform .

The PD-250L is based on the Proxflyer MAV shown in Fig.6 but has better performance.

The helicopter has been developed by the company Prox Dynamics AS in order to increase the interest for passively stable helicopters and to fuel interest for MAV related science. For non-commercial use, universities and labs can download free drawings and specifications to build their own flying platforms or they can buy complete ready to fly helicopters.

5.1. Specifications

The helicopter uses a slightly modified rotor compared to the earlier Proxflyer type helicopters. Two of the rotor blades are connected to the ring with pivots and the coning is reduced. The changes allows for a higher forward speed while the passive stability is kept unchanged. The helicopter has a double tail with two "tilting" motors giving the helicopter the same maneuverability as other helicopters. To fly sideways (roll control) the two tilting motors are run in opposite directions to create a sideways tilting momentum. To fly forward (pitch control) the motors are run in the same direction.

The helicopter is not equipped with any yaw gyro and depending on the application this will have to be part of the payload or control system implemented on the helicopter.

Lifting capacity and typical flight times will vary depending on the weight and capacity of the battery. The specifications for the PD-250L equipped with a 2-cell 7.2 V, 650 mAh lithium polymer battery (weight 35 gram) are:

Rotor diameters:	250 mm
Max length:	350 mm
Height:	140 mm
Weight without payload:	90 grams
Maximum payload:	40 grams
Flight time (120g):	10 minutes

If the payload is powered from the flight battery the flight time will be reduced according to the power drawn by the payload. For operations in high altitude (above 1000m) the flight times must be expected to decrease.

5.2. Typical use and applications

Typically an inherently stable flying platform like the PD-250L helicopter is used in indoor labs and test areas with no wind or turbulence. Applications will include:

- Autonomous control and navigation
- Flight pattern studies
- Obstacle recognition and avoidance
- Testing of systems for vertical control
- Swarm studies
- Interaction with other kinds of vehicles
- Stereo vision control

5.3. Availability

The PD-250L is a relatively simple design with few critical or complicated mechanical parts. Most engineers, lab technicians or students will be able to build their own helicopters. For non-commercial use it is possible to download a full set of drawings, part lists and specifications from the Prox Dynamic AS web site (<http://www.proxdynamics.com>).

Complete ready to fly versions of the PD-250L will also be available.

6. FUTURE DEVELOPMENT

Outdoor version: The current Proxflyer helicopters are completely stable with respect to the surrounding air. This limits the possibilities for operations under windy conditions. Work is under way to try to maintain some of the inherent passive stability and at the same time reduce the influence of wind and turbulence. It might, however, prove to be very difficult to achieve this without some kind of active control of the rotor blades.

The early Mosquito helicopter had an electronic compass to control the heading. The compass utilized a 2-axis magnetic sensor from Honeywell. This sensor was connected to the control and mixing micro controller onboard the helicopter and the yaw input from the remote controller was used to adjust the desired heading with respect to magnetic North. A control routine then adjusts the differential speed of the counter rotating rotors to maintain the desired heading. Experience has, however, shown that the Earth's magnetic field is very easily disturbed inside buildings and therefore the electronic compass was not reliable for indoor use. Future work is planned to combine a 2 or 3-axis compass and gyro sensors to improve the indoor navigation capabilities.

For remote operations inside a building it has been demonstrated that keeping the correct height is probably the most difficult task. If the UAS is controlled by the feedback from an onboard camera it will be essential to have additional guidance from sensors giving height information. Preliminary studies indicate that it is possible to have precision pressure sensors with a resolution of less than 100 mm for relative height measurements. One of the challenges using a sensor like this is the pressure differences in the down-wash from the rotors and variations in air pressure in the building. Future plans for improving the height control involve both the use of a pressure height sensor and a MEMS accelerometers.

7. CONCLUSIONS

A passively stable indoor hovering UAS is possible. By utilizing ideas demonstrated in different Proxflyer helicopters, it is possible to achieve hovering flight that is completely stable with respect to the surrounding air. Such helicopters are efficient and easy to operate and seems to be a good flying platform for several applications related to future UAS research and development.

8. REFERENCES

- [1] Proxflyer AS www.proxflyer.com
- [2] Rotor and Aircraft Passively Stable in Hover US patent US7204453.
- [3] Interactive Toy Concept www.interactivetoy.com
- [4] Swarm of Miniature Aerial Vehicles by De Nardi, Holland, Woods and Clark. University of Essex. <http://cswww.essex.ac.uk/staff/owen/newultraswrm.pdf>
- [5] Stereoscopic Flat Panel Display by Jones, Kirsch, and Johnson, Redstone Arsenal, AL. Dec. 2004.
- [6] Prox Dynamics AS www.proxdynamics.com