LINKMAV, A PROTOYPE ROTARY WING MICRO AERIAL VEHICLE

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Abstract: This paper provides an overview oabout the design of the LinkMAV rotary wing autonomous Micro Aerial Vehicle. The paper describes the flying platform, the main problems related to aerodynamics and propulsion, the onboard avionics and the flight control system, including the autonomous navigation algorithms. We also describe the sensor chosen for the MAV05 competition, held in Garmisch Partenkirchen, and a high level system and multi-modal interface providing more advanced autonomy in terms of collision free path planning and in-flight mission reconfiguration.

Keywords: Helicopter, Design, UAV dynamics, control and navigation.

1. BACKGROUND

The Autonomous Unmanned Aerial Vehicle Technologies Lab (UAVTech) at the Department of Computer and Information Sciences, Linköping University, Sweden, has recently begun research and development in the area of rotary wing micro air vehicles. The intent is to combine this R&D with earlier work where Yamaha RMAXs were used as a research platform. The long term goal is to develop a multi-platform fleet of both aerial and ground vehicles to be used as a testbed in future research with cooperative multi-platform fleets of robotic systems.

The LinkMAV (see Fig.1) is the first MAV developed by UAVTech. LinkMAV was originally conceived as an add-on to the RMAX where it could be flown to a location and deployed by the RMAX to fly around and inside building structures. The LinkMAV has recently been modified to meet the requirements for the MAV 2005 event in Garmisch Partenkirchen, Germany, Sept, 2005 (ref. ((2))). Although not designed specifically for it, its flexible design permitted a graceful modification of the original platform to meet the stringent specifications for the competition. The LinkMAV won the competition as "best rotary wing" MAV.

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2. THE PLATFORM

2.1 Design drivers

A number of requirements were set and assumptions made at the beginning of the design process which drove development of the LinkMAV in a particular design direction:

- Full automation: the ability of stabilize and navigate the platform without human intervention is a basic requirement to reduce the

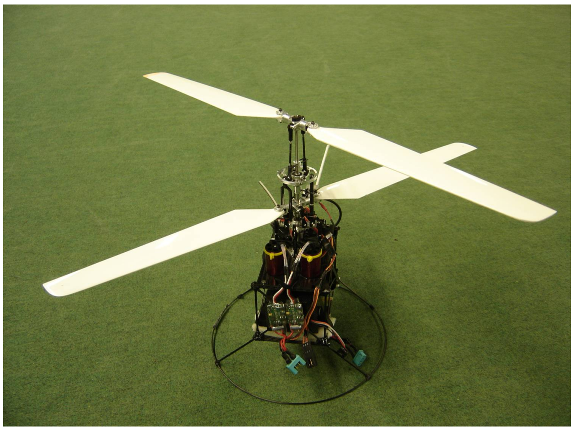

Fig. 1. The LinkMAV rotary wing micro aerial vehicle

criticality of the control data links and to conduct missions out of line of sight. This implies that at least an autopilot must be embedded into the design. This point is central to the LinkMAV design, since much existing research with deployed MAVs tend to be exercises in pure miniaturization. Such focus does not take into account the need for automation. Moreover, full automation, in terms of automatic stability, control and navigation, is a minimum baseline for more advanced autonomy.

- Mission re-configurability (in-flight re-planning): whatever the level of autonomy a platform has, the operator should be able to reconfigure mission goals during the flight. Thus implies the need for an onboard data-link for communication during mixed initiative missions with human operators.
- Rotary wing configuration: this is a natural choice for a requirement of low speed flight and hovering capability, necessary for the types of missions we have in mind, but also appealing for the following additional reasons:
  - Flight at low speed and the ability to hover enable closer interaction with the environment in terms of situational awareness, which is useful for advanced autonomy where high-level functionality sometimes requires larger temporal windows.
  - Platforms able to hover and/or "perch and steer" are potentially suitable for a large number of practical civil applications (such as power line inspections, inspections of bridges, small scale photogrammetry, accident and catastrophe reports, etc.).
  - Rotary wing platforms are currently the most feasible solution for indoor applications;
- Electric power system: electric power plants are reliable, silent and clean, and thus suitable even for indoor operation; the energy and power density of the last generation of Lithium Polymer batteries allows for considerable endurance even for outdoor applications;
- Maximization of payload and endurance: efficient experimentation with autonomous and cooperative behaviors demands robustness of the platform, long flight times, and the possibility to embed sensors and perceptive devices of acceptable quality;
- COTS based system: sub-optimal solutions can be initially accepted if rapidly available, while the optimization of each component can be left to later design iterations.

The choice of configuration is primarily driven by the need to maximize payload and flight time. Three configurations have been analyzed in the preliminary design phase: a classical helicopter-like main rotor - tail rotor configuration, a coaxial counter-rotating configuration and a four rotor configuration. The coaxial rotor configuration is the most efficient: if the two rotors are properly tuned (correct speed and relative collective setting), the configuration is 5% more efficient than a four bladed rotor of equal solidity, and up to 30% more efficient than a conventional helicopter equally loaded (Ref. (1)). The absence of a tail rotor results in the rotor system using all of the engine power for lifting purposes which in turn maximizes the payload capability. Ducted fans have not been considered, since their behavior in windy and gusty conditions is unknown. Some research shows that ducted fans can be significantly more efficient than un-shrouded rotors from an aerodynamic point of view, but the overall tradeoffs which take into account the additional weight required for the duct do not appear to be available in literature for analysis.

The fundamental low Reynolds number issue argued for as large a vehicle as possible. The initial weight budget estimations showed at an early stage that the design margins for an autonomous rotary wing MAV (still classifiable as "micro") where very limited. Consequently, the rotor diameter was preliminarily set to 50 cm. The commercial availability of a large variety of potentially suitable rotor blades of this size froze this parameter in the early stages. Estimations on rotor solidity and the Reynolds number led to the choice of two-bladed rotors.

Mechanical complexity, which is a known Achilles' heel for coaxial helicopters, has been minimized by:

- A twin engine configuration, one for each rotor. Single engine solutions need a relatively complex and heavy gearbox to provide the two rotation directions.

- Electric brushless motors are particularly suited for this application, since the rotation direction can be inverted simply by switching the polarity. This results in the following advantages:
  · the airframe design can be kept symmetric (shape, balancing);
  · Identical motors and gears can be used for the upper and lower driving chain, simplifying the maintenance of the platform (fewer spare parts).
- No differential collective: yaw control is achieved by differential rotor speed control.
- No Bell-Hiller stabilizers, but active stabilization is provided by a digital control system.
- The design is aerodynamically neutral in yaw from all directions, i.e. there is no aerodynamic front or back of the platform. This avoids the need for a pan mechanism for the sensor, since the whole fuselage can bee pointed in one direction while the helicopter flies in a different direction.

A number of issues have shown to be particularly worthy of discussion during the MAV design phase and iterations. Here are the most relevant:

- Thin blades can be more efficient at low Reynolds numbers (the same tendency has been demonstrated for fixed wings), and thin blades may also be a good choice from a weight minimization perspective. But reducing the weight of the blades, and thus their moment of inertia, increases the Lock number and reduces the rotor time constant, making the control task more challenging. Aerodynamic efficiency may conflict with controllability.
- Efficient rotors should be very lightly loaded, but low disk loads make the MAV more sensitive to turbulence and wind. For a given thrust, a MAV with smaller rotors may be less affected by wind gusts than one with larger rotors, but the latter will have longer endurance. Aerodynamic efficiency may conflict with operational requirements.

2.2 Platform description

The LinkMAV is built of the following subassemblies:

- Chassis, including the main support plate, the avionics cage and the landing gear. The chassis is entirely built out of carbon fiber. The main support plate has the function of connecting the engines and the rotor heads, giving stiff housing to the reduction gears. The avionics cage provides supports for the avionics box, and some protection to shocks and vibrations. A number of landing gear configurations have been studied and tested, leading to a "landing ring" design.
- Rotor heads, including the hollow shaft of the lower rotor, the shaft of the upper rotors, the two swash-plates with linkages and a support to the chassis. Two large identical 176 teeth gears, one for each shaft are mounted on the bottom of the shafts. The torque-balanced coaxial rotors eliminate torque reactions on the fuselage, thus making the chassis a totally independent body from the rotor-transmission-engine combination.
- Power drive which includes two RZ Micro-Heli v2.0 brushless electric motors, each equipped with a 10 teeth pinion and two CC phoenix 10 speed controllers. Each motor can generate up to 85 W, with a maximum efficiency of 0.86.
- Avionics box is a carbon fiber box housing the most valuable part of the avionics (mainly the autopilot), with provisions for passive damping of shocks and vibrations. The box is housed into the avionics cage of the chassis.
- Avionics package.
- Lithium-Polymer main battery pack, which powers the motors.
- Lithium-Polymer avionics battery pack, which powers the avionics and payload.

Table 1. Platfrom weight breakdown.

Item	Weight [gr]
Power Drive	66
Rotor heads	79
Rotor Blades	40
Chassis	86
Servos and Receiver	39
Avionics	80
Avionics and Video Battery	17
Platform Empty Weight	407
Video Equipment	26
Data Link	21
Main Battery	47-400
Platform Take Off Weight	500-900

The platform weighs 407 grams, without main battery and without payload ("empty weight"). A virtually infinite number of payload and battery combinations can lead to a total weight of up to 900 grams, which is the heaviest configuration tested in flight so far.

2.3 Crashworthiness

The avionics package (mainly the autopilot) represents more than 80% of total material costs. Even if the working hours needed to assembly the system are not computed, it is obvious that good crash worth design principles should be adopted in order to protect the autopilot. This has been done by placing the autopilot board inside a protective box (previously referred to as ”avionics box”) built of carbon fiber plates. Inside this very stiff box, the autopilot is suspended on damping supports of foam. The avionics box itself is then housed within the carbon rod construction of the lower part of the chassis, suspended on isolating supports. Other factors contributing to the crashworthiness of the design are: (1) The battery pack hangs below the fuselage and can easily detach in case of vertical impact with terrain; (2) the motor and the relatively heavy rotor head mechanics, which necessarily have to be located above the avionics, are mounted on a very stiff carbon fiber plate which can transfer the inertial loads to the avionics box in a distributed manner, in case of collapse of the chassis; (3) the upper rotor shaft is relatively weak, and tends to bend in correspondence of the upper ball gearing in case of accident. This usually causes the interference of the upper and lower rotor, with the consequent destruction of the two colliding blades. The kinetic energy of the spinning rotor is spent in deforming the blades, and no loads are transferred either to the chassis or to avionics box.

2.4 Aerodynamics

Untwisted tapered off-the-shelf plastic blades with a symmetric airfoil have been chosen, primarily due to their availablity on the market and to the possibility of using them both on the upper and lower rotor: twisted blades would in fact need to be available in two mirrored shapes.

To better dimension the power system, and to understand the margins for improvement for future developments, an experimental investigation on the efficiency of small dimension rotors has been conduced. A test rig has been built in order to direct measure thrust, torque and rotation speed of rotors, in order to be able to calculate aerodynamic thrust and torque coefficients. The tests have been conduced only on two-bladed rotors, where the goal was to understand the efficiency trends of different blades. The general conclusion of this investigation (the details of which are going to be published in a separate paper) is that a figure of merit of 0.50 can be expected from such a small rotor using off-the-shelf blades. Some margin of improvement can be expected with twisted and properly tapered blades, especially if using thin cambered airfoils. At 2000 rpm, the tip Reynolds number at sea level is around 120000, while at the maximum chord station (close to the root) it’s 40000. Changes of the aerodynamic

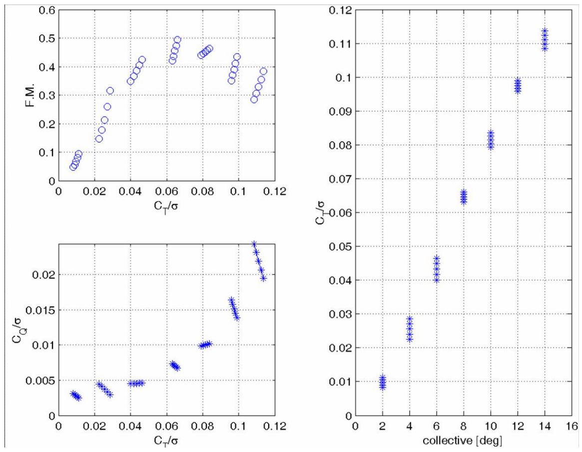

Fig. 2. Aerodynamic properties in hovering of the LinkMAV blades, tested on a 2 bladed rotor. For each collective pitch setting the results relative to 5 different rotor speeds are reported on all graphs, corresponding to 500, 1000, 1500, 2000 and 2500 rpm. The best performances (higher CT and F.M. and lower CQ) correspond to the highest speed.

coefficient CT and CQ vs rotation speed have been observed mainly below 1000 rpm (tip speed Reynolds number below 60000). Above 1000 rpm the coefficients have kept substantially constant, with CT slightly increasing and CQ slightly decreasing. This produced on all blades an improvement of the figure of merit at the higher angular speeds.

The power required for hovering is calculated as:

$$P_{hovering} = \frac{P_{ideal}}{F.M.} = \frac{1}{F.M.} T \sqrt{\frac{T}{2\rho A_D}}$$

The light configuration of the LinkMAV, weighing 500 grams, requires therefore 45 W to hover, assuming a conservative figure of merit of 0.45. A heavier configuration, weighing for example 800 grams, would require 70 W.

2.5 Propulsion

Power to the LinkMAV rotors is supplied by two RZ Micro-Heli v2.0 brushless electric motors, from Razor Motors. Fed at an average voltage of 10.5 V (3 Lithium Polymer cells), the motors can deliver an efficiency of up to 86%. A single stage reduction gear, consisting of a 10-teeth pinion and a 176 teeth gear provides a rotor/motor revolution speed ratio of 17.6:1. The nominal hovering set point for the light version of the LinkMAV corresponds to a current of 2.1 A: the motors spin at 44000 rpm and the rotors at 2500 rpm.

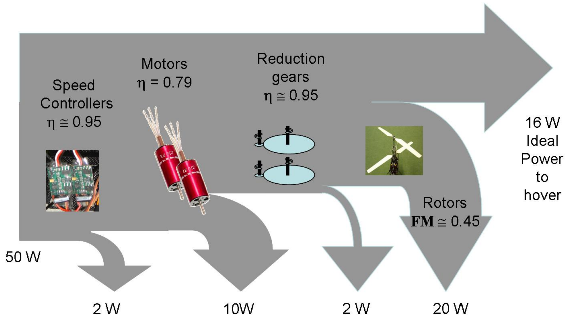

Fig. 3. Performance and efficiency of the RZ Mini-Heli v2.0 electric motor, fed with 10.5 V

3. AVIONICS

3.1 Hardware

The core of the onboard avionics is a Micropilot MP2028g off-the-shelf autopilot. The autopilot includes 2G 3-axis accelerometers, a 3-axis rate gyro, two pressure gauges (only the static port is currently used) and a GPS receiver. The autopilot is to some extent programmable by the user, by setting gains on predefined PID loops and even for creating new PID loops. The autopilot board provides the capability of recording 47 parameters at 5 Hz. Telemetry is also supported when a data-link is coupled to the board. 100 user definable parameters can be down-linked, at 5 Hz. This feature of being able to reschedule and fine-tune the control system gains in-flight has proven to be very useful. A magnetic compass provides heading information, which is essential for GPS-aided autonomous hovering. The MAV is equipped with a high-resolution micro board color CCD camera which is connected to an analog video transmitter (composite video). A digital video processor controls shutter time, signal gain, and white balance. It is configured through an I2C interface. Depending on the mission lenses with different focal lengths and optical filters can be chosen. The camera is mounted directly on the lower part of the chassis pointing forward with a fixed tilt angle.

3.2 Operating modes

The LinkMAV can be operated in 3 modes: Back-up mode, Manual Ordinary mode and Autonomous mode. The operator can switch to and from any of the modes during flight.
Back-up mode: the control signals are sent directly from the standard RC transmitter to the 3 servos and to the motor controllers, by-passing the MP2028g. In this mode the platform is highly unstable in pitch and roll, and no automatic stabilization of the heading is provided.
Manual Ordinary mode: the control signals from the RC transmitter are interpreted by the MP2028g

Takeoff ***Climb 40*** ***Flyto (50, 60)*** ***Wait 100*** ***Flyto (0,0)*** ***Repeat -1***	The platform takes off and climbs to 40 m (altitude relative to power on altitude). It flies to a waypoint located 50 m east and 60 m west relative to the origin. It then hovers there for 100 seconds, and flies back to the starting point, where it hovers until the operator intervenes.

Fig. 4. Example of mission file (left) with expected behavior (right)

as target pitch and roll angles, thus allowing direct attitude control. The operator control in yaw is interpreted as target heading (heading hold with centered stick). In calm air (indoor) this allows to hover "hands-off", since the platform is in practice neutrally stable in position (once stablized by the control system).
Autonomous mode: it includes autonomous hovering and "hovering-to" waypoints. The navigation algorithm that is currently supported by the Micropilot firmware for rotary wing platforms is basically a hovering algorithm that calculates pitch and roll target angles based on the offset from the target hovering point. The same logic is currently implemented for navigating between waypoints by introducing a limitation to the maximum allowable target attitude angles. The drawback with this solution is that by not being able to track a nominal trajectory, the effect of a cross wind is not compensated for. This results in non-optimal paths. In autonomous mode the altitude channel can be slaved to a mission plan (a commanded altitude profile, specified in the mission file), or it can be handled fully manually by the operator. In this way, while position and heading are handled autonomously according to the mission plan, the operator can climb and descend interactively by acting on the RC transmitter.

3.3 Reconfiguration and collision avoidance

When flying autonomously, the mission specified in the mission file can be reconfigured during flight assuming of course that a data-link is installed. Depending on the degree of autonomy required, flight trajectories can be programmed by interactively moving, adding or removing waypoints on a moving map presented to the operator on a laptop, or automatically generating a segmented trajectory via a motion planner. Under the assumption that an accurate 3D terrain database exists or can be generated, collision-free trajectories are generated on-line, during the execution of the mission. No-fly-zones and obstacles can be interactively added to the database during flight, and taken into account when generating new trajectories. The MicroPilot board is configured to use a modem to communicate with Horizon Ground Station software provided by the MicroPilot company. In order to supply the DRS with telemetry data and the MAV with commands a custom ground station interface was developed using the multiuav.dll library, which is a part of the MicroPilot XTENDER software development kit. This interface communicates with the Horizon using TCP/IP Ethernet connection. The use of the Horizon Ground Station software is not necessary because the implemented interface can directly communicate with the MicroPilot board using a modem. The mission planning service is supplied with the telemetry data necessary to determine MAV's initial configuration and the goal position is selected by an operator using multimodal user interface. Path planner service delivers collision-free path which consists of straight line segments and appropriate waypoint positions are transited to the MicroPilot board. The executed flight plan can be at any time exchanged with a new one achieving full in-fight mission reconfiguration.

3.4 Flight Controls

Attitude control is provided by conventional swash-plate mechanisms, one on each rotor. The upper and lower swash-plates are mechanically connected to generate the same pitch and roll angles and are operated by three servos in a 90 degrees configuration. Both the upper and lower rotor heads are flybar-less, i.e. the Bell-Hiller mechanism usually used on model helicopters is not used. Those mechanisms are almost universally adopted on model helicopters to slow the attitude dynamics down to levels that can be compatible with the control bandwidth of a human pilot, by producing lagged rate (or "pseudo-attitude") feedback in the pitch and roll loops, stabilizing the low frequency dynamics ((3)). The LinkMAV platform is unstable in pitch and roll. Hovering with fixed sticks triggers a phogoid mode rapidly divergent (see Fig.5). Instead, stability is provided to the LinkMAV by the onboard digital control system. PD independent control loops in pitch and roll provide attitude stability without the need of cross-coupling terms.

Vertical control is provided by collective pitch inputs, generated by the three servos, and transferred to the two rotors by the swash-plate mechanisms. Each rotor receives the same collective input. The collective setting on each rotor is mechanically adjusted by tuning the length of the linkages connecting the lower and the upper swash-plates, in order to provide about 1 degree more pitch to the lower rotor, to take into account the inflow velocity of the upper rotor. Throttle and collective inputs are statically scheduled in order to achieve constant rotor speeds with varying collective settings. Yaw control is obtained by

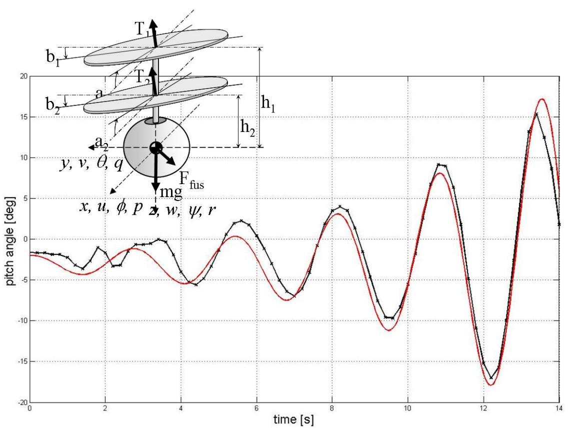

Fig. 5. Simulated and measured fixed-stick attitude dynamics. The details of the simulations model are bejond the scopes of this overview paper.

differential speed control on the two rotors (not by differential collective). This sensitively reduces the mechanical complexity of the rotor head.

3.5 Conclusions

The LinkMAV should be considered as a platform in the early stages of development with many iterations left to do before we achieve satisfactory and robust performance. The UAVTech group plans on continuing along this track of research and the MAV 2005 competition has provided a great opportunity to help in this development.

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