Aerial tethered robotic system with hovering-hopping agents for security and rescue operations

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14 Aug 06 ***Abstract* – This paper discusses the design and control aspects for an aerial robotics system that has the potential to solve special needs experienced in difficult rescue and security operations. The system is composed of an aerial host platform, a tethered robot and hovering agents. The host platform is a robotic aerial vehicle that can fly to the area and shift to hovering at a safe altitude above the targeted object. The tethered robot is lowered from the platform via a long cable to survey the object. It can deploy the expandable robotic agents to explore the object by entering it and proceeding in a hovering-hopping mode while relaying wirelessly the navigational data - via the tethered robot and the host platform - to the operators sitting in a safe control position. The paper focuses on the conceptual design of the robotic system and also relates to our work to build a Simulink dynamic model of the agents.**

Index Terms* –*aerial robotics, tethered robot, hovering agent, gravity stabilization, free gimbal system, gyroscopic effects

1. DRIVING IDEAS BEHIND THE PROJECT

The concept of the aerial system (Fig. 1) was inspired by deep sea marine robotics where a host ship uses a tethered robot to survey the site of a shipwreck and deploy tiny robotic agents from the tethered robot into an opening within the sunken vessel.

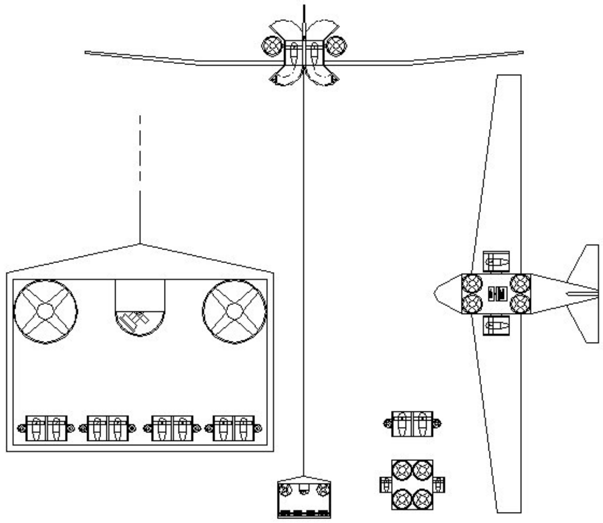

Figure 1 – The concept of the aerial system composed of a flying-hovering platform, a tethered robot and hovering-hopping agents.

Figure 2 – Animation of the system approaching a disaster area.

Our aim is to apply this approach to aerial robotics scenarios while working on land, sea and even under water. Applications could include search and rescue or security operations [1, 2] over a disaster area on land, marine rescue or marine security operations and under water rescue or security operations. An aerial platform hovering at high altitude [3, 4] would deploy the electric powered tethered robot to survey targets on the ground, such as buildings and cars, and would

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deploy the hovering-hopping agents to enter said targets. These agents would pull light weight powered cables to extend their battery life-spans.

The conceptual analysis of the system and early experiments of stability was presented at SPIE'2004 [4].

Figure 3 – Animation of a hovering-hopping agent exploring a collapsed structure.

2. POTENTIAL OF THE SYSTEM

The potential of this system is really enormous. The robotic system could be also used to pickup pilots who ejected from their aircraft over the enemy territory. It could even be applied to save stranded submarine crews from the ocean bed when rough seas hinder other marine efforts. The unique capability to explore streets and structures and even pickup or put objects with human interaction could start a new era of change in military thinking.

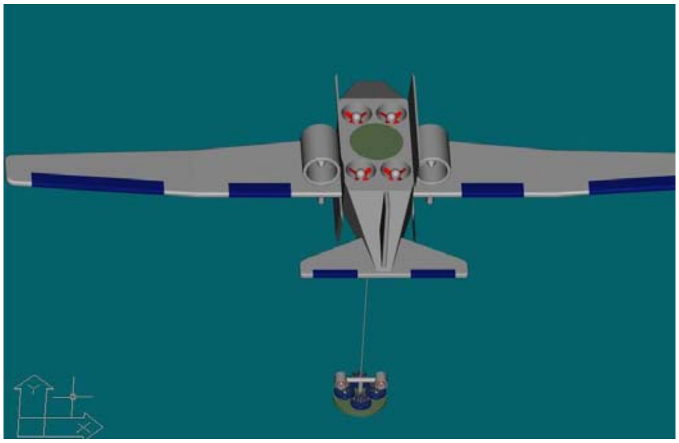


Figure 5 – CAD illustration for the platform hovering mode.

The aerial system could also apply the tethered robot to observe maritime targets like ships and even used to pickup survivors from a sinking ship or survivors in the water in a very rough sea. The maritime applications could even be expanded to underwater observations of ports conduct rescue operations when stormy sea hamper access of ships to submarine disaster area.

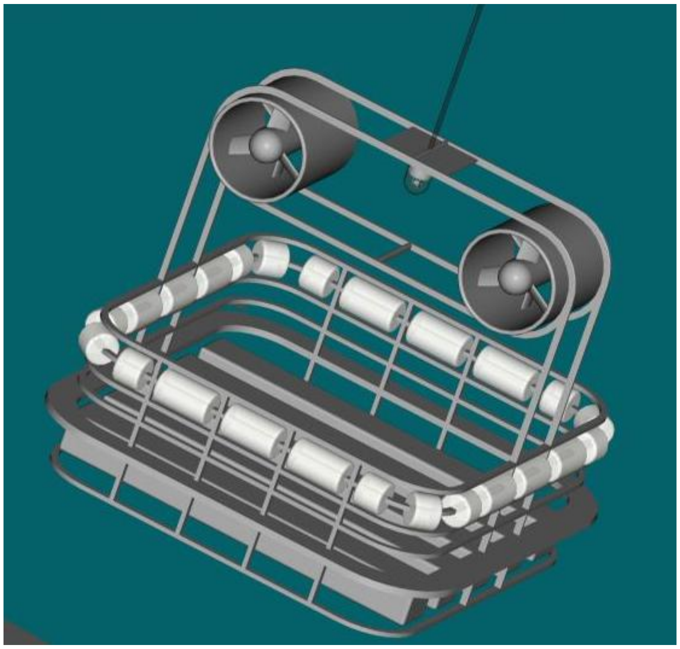


Figure 4 – The concept of applying a tethered robot for rescue operations in maritime disasters.

The advantage of this approach over the conventional approach of employing manual labour for search and rescue, is that these agents would be able to enter confined spaces inaccessible to humans and, being expendable, could be used to investigate regions that would be too risk laden for people to examine. This is especially advantageous when dealing with the aftermaths of an earthquake or bomb blast where buildings are structurally unstable and rescue teams would run the risk of causing injury to both themselves and those they would rescue were they to walk amongst the debris. Even when compared to the use of helicopters, which traditionally would be the only way to provide access to inaccessible targets, the agent approach has advantages.

Helicopters create significant downdraft which could cause unstable structures to collapse and the noise they generate makes it virtually impossible for victim's trapped beneath rubble to alert would be rescuers to their plight. Deployed agents would suffer from neither of these drawbacks as their electrically powered motors would allow relatively quiet observation and interaction with survivors trapped in the ruins.

3. EXISTING TRENDS FOR AERIAL ROBOTICS

There is a very clear trend in the world to increase the use of unmanned aerial robotics system especially for security and SAR missions. The R&D efforts devoted to improve new generations of UAVs around the world are enormous. Almost any risky or routine mission could be handled efficiently by robotics in general and aerial robotics in special. On this background we believe that the effort to expand the application envelope is so important and appropriate timed for governments around the globe.

4. R&D CHALLENGES

The challenges involved in R&D of the system (even a feasibility demonstrator) are touch. We are talking about a robotic system which is composed of three parts: a host platform, tethered robot and deployable agents. Each component needs unique solutions to overcome many problematic issues.

a. Hovering-hopping agents

The hovering-hopping robotic agent is a tiny aerial vehicle designed to be able to fly into confined spaces of collapsed structures. The biology inspiration is derived from the capability of bats to navigate in dark caves. Our flying bat should survive bumping into walls and collision with obstacles. It should be able to land and take off from the rubbles that cover the floors. It also should be able to drag a power line to extend the vehicle range dictated by its battery capacity. The power line could be used to help in the navigation similarly to cave explorers. Ruins are clutters with many obstacles and the environment is difficult as smoke and dust may hinder vision while the still in the concrete may hinder using magnetic compass. The fact that the serial vehicle is tiny and designed for one mission cycle (the assumption is that it may be difficult to retrieve the agent and prepare it to another mission) does not mean that the R&D challenges are much smaller than large and durable robotic system. Even the building blocks for such vehicle do not really exist. There is a need to develop efficient counter rotating ducted fan units with high quality motors and proper cooling systems. The ducted fan units which we are currently using for feasibility demonstrations are taken from RC toys and are not suitable as a on the self component. Our aim is to implement our Titan 4WD outdoor mobile robot experience in using the CTFM ultrasonic sonar for outdoor navigation to the navigation of the agents.

b. Tethered robot

The tethered robot is a long flying pendulum. The pendulum is inheritably stabilized by the gravity field. The main concerns are avoiding the pendulum to swing due to motion of the platform or affect of the wind. Our plan is to stabilise the yaw around the twisting cable using gyro closed loop. We believe that if needed it will be possible to stabilise the swing angle by actively using the propulsion systems attached to the pendulum.

c. Flying-Hovering platform

Currently a few platforms are under development to achieve unmanned flying combined with a hovering capacity. Prominent projects are the Eagle Eye by Bell Helicopters, Fire Scouts by Northrop Grumman and a joint venture of Urban Aeronautics and Bell Helicopters for unmanned version of the X-Hawk. Our perception for such a platform is based on electric powered propulsion units. We were thinking about hybrid air vehicle which can fly efficiently as a fixed wing aircraft using two pulling electric ducted fans. To shift to hovering mode the four lifting units are exposed by opening doors. We feel that the technology exists but intensive R&D effort is needed to implement this vision.

The Israeli company Steadycopter is developing an unmanned helicopter robot which could be a good candidate for conducting evaluation tests especially to carry a miniature gravity stabilised seeker head (see but not being seen …). The robot has a fully computerised navigation system and capable of precise hovering while deploying a tethered seeker head for close-up observation. It demonstrated autonomous take of & landing

d. Communication networking

Above the technical challenges associated with building the flying components of the system is waiting the greatest challenge of control and communication in the system level and clusters of systems level. If our conceptual thinking will be proved successful, the technology will be spread in civil and security services and the main concern will be to operate groups of systems on a national base.

5. LEARNING FROM RC TOYS & ROBOTS

During the on going research we gained the inspiration for the feasibility of using gravity stabilisation to the agents by looking at many existing and past time aerospace and hobbies projects. Interestingly, one can gain inspiration just by watching RC toys that are a law cost but still demonstrates the same principles of physics used by multi-million budget aerospace projects.

The tiny hovering robot developed by Epson in Japan is using a counter rotating coaxial rotors. We believe that the stabilisation around the pitch and roll axis are achieved by the low centre of gravity. The yaw stabilisation is employing a solid state rate gyro feedback control. The forward and lateral motion is achieved by shifting weight which tilt the system and generates a horizontal thrust component. There is a nice video clip in Epson's web site.

The AirScooter personal helicopter is using a very similar design principle. Instead of shifting a weight the lifting system is gimballed with respect to the chassis that holds the pilot and motor. The effect is similar. To get a fine yaw control they employ control surfaces in the tail under the vertical down stream of the rotors. The basic principles are also implemented in AirScooter RC toy. The video clips in their web site demonstrate the motion control of the manned and unmanned version.

Figure 6 – RC toys used to investigate hovering & flying qualities. The Blade Runner is on the left while the Hirobo Lama on the right. In the middle is the Parallax micro used to link the RC transmitter to the computer. We use LabVIEW virtual control panel to command the toys.

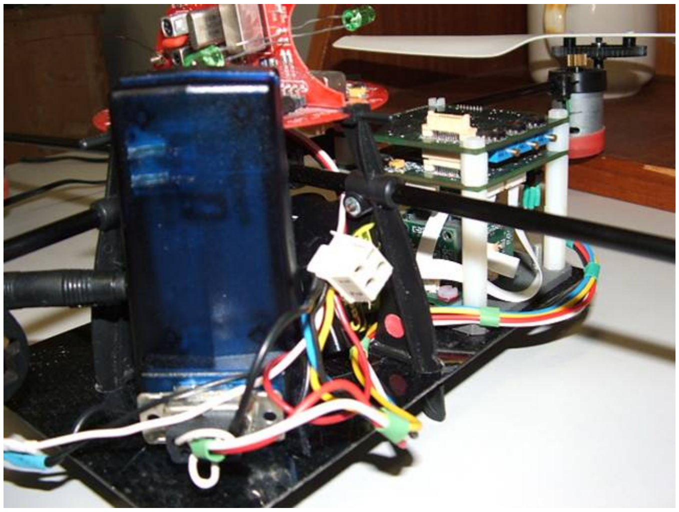


Figure 7 – We are using the 3 axis solid state gyro stabilized Dragan Flyer to fly & test our INU developed by CSIRO Brisbane (Dr. Peter Corke).

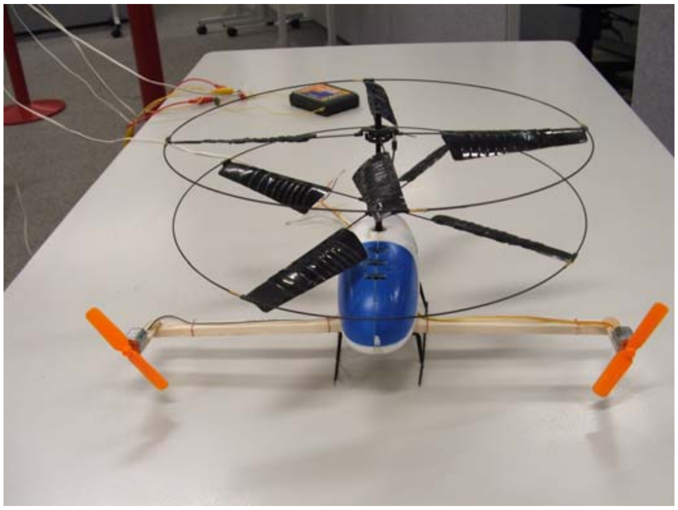


Figure 8 – Modified Blade Runner to emulate the design concept of the agent. The same propulsion units will be packed in a foam envelope with Russian dole stability.

Figure 9 – The flying saucer illustrates interesting concept of a free gyro since no gimbal bearings are being used to support the spinning disk.

Trek Aerospace are using a lifting system composed of a pair of counter rotating ducted fans located side by side instead of coaxially. They built a manned and unmanned electric version and the video clips in their site demonstrate the stability gained by the gravity effect of a flying pendulum.

Even a very cheap RC toy like the Blade Runner is amazingly stable without employing any rate gyro. The lifting system is composed of a coaxial counter rotating propellers. The motors and battery are located very low which creates an inherently stable hovering (even too stable judging from the video clip …). The horizontal propeller in the tail applies a pitching moment (similar to the effect of shifting weight).

To enhance our design we conducted many experiments with four RC commercial available systems: The four rotors Dragan Flye, the Hirobo counter rotating co-axial SR Lama Helicopter, the Blade Runner helicopter and the Flying Saucer.

6. BUILDING FESABILITY PROTOTYPES

To assess the potential in the driving ideas we built and tested a few simple feasibility prototypes and we are currently in a process of design and research of more advanced models. The system is a long tern research effort and the progress in research is done by improvements of models and subsequent tests.

The robotic system is composed of three parts: a host platform, tethered robot and the hovering-hopping agents. The main idea behind the concept is to separate the functions of each component. The role of the host is to be able to fly to the relevant area and hover above the targeted object whilst deploying the tethered robot to the vicinity of the object.

Figure 10 – Conceptual design of the tethered robot with propulsion configuration of pulling unit to produce the swing control and two counter rotating units at the tail to produce preloaded yaw control.

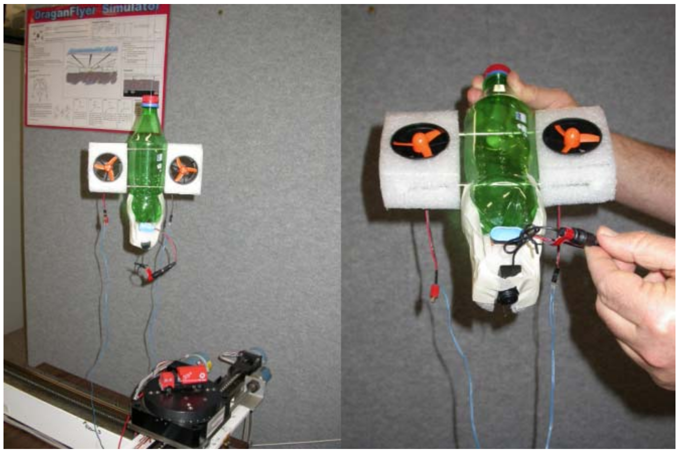


Figure 11 – Conceptual design of the tethered robot with propulsion configuration of side by side counter rotating pulling units to produce cross-coupled but compact design for the swing control and yaw.

The tethered robot is essentially a very long, gravity stabilized pendulum that contains the sensors powered by batteries. The lifting is done by the cable whilst local manoeuvrability is achieved by applying ducted fan units, vectoring the tethered robot relative to the vertical cable. The long cable, which could simply be made from strong fishing line, provides a friction free gimbal system and free damping from induced vibrations of the host platform.

The dynamics of the tethered robot are derived from a case of double pendulum expended to a 5 degree of freedom system based on four angular movements on a sperical envelope plus another angular position of the thrusters with respect to the cable's plan and robot's body cone.

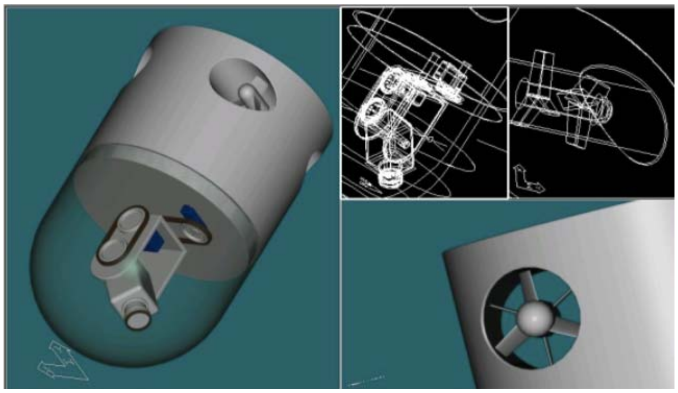


Figure 12 – 3D CAD solid modeling design for the concept of applying a tethered robot for reconnaissance operation.

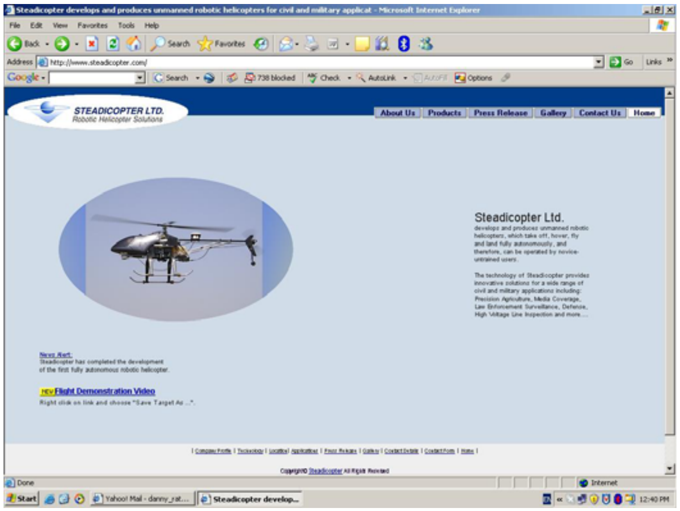
The basic slow mode is derived from a concentrated mass point moving on the long cable. The faster mode is derived from the mode of a short rigid pendulum consists of the robot's body inertia. There is also a twisting motion of the robot's body on the cable flexibility. All these issues plus details of the construction of the prototype (including the sensor suit) are a subject of another paper being written.

Figure 13 – The prototype of the tethered robot (left) and a close up on the dome (right) which accommodate a wireless camera on pan & tilt unit.

The robotic agents are deployed from the tethered robot to explore the targeted object. They can enter via relatively small openings and hover into the confined spaces of collapsed structures and land on the floors. The vertical fans provide the lift while the side by side fans provide forward motion and turn (yaw) control.

The concept of the custom made robotic UAV platform should include the capability to fly to the target area, switch to hovering mode and deploy the tethered robot containing the agents to the vicinity of the target. The platform (as well the other components – the tethered robot & hovering-hopping agents) should feature a low audio and thermal signature. Our design (Fig. 5) for the hovering host platform is inspired by leading projects such as the Boeing-Bell tilt rotor V-22 Osprey [5, 11] and the X-Hawk aerial vehicle [6]. The design philosophy of our robotic platform is of a hybrid UAV that retains the features of long range UAVs (flying economically to long distances), but can also switch to hovering mode for short sessions. All the six motors in the platform in Fig. 1 are electrical and being fed by a light weight generator unit of petrol or turbine engine. For feasibility tests and other evaluation experiments, we plan to use a large RC helicopter owned by the helicopter officer of the Illawarra Model Aero Club – Mr. Steven Fenton who brings with him a wealth of experience in flying and testing RC vehicles. We already conducted a series of experiments using a high building in different wind conditions.

Another candidate for future evaluation tests of the tethered robot could be the Israeli company Steadycopter.



Steadicopter Ltd.
develops and produces unmanned robotic helicopters, which take off, hover, fly and land fully autonomously, and therefore, can be operated by novice-untrained users.

The technology of Steadicopter provides innovative solutions for a wide range of civil and military applications including: Precision Agriculture, Media Coverage, Law Enforcement Surveillance, Defense, High Voltage Line Inspection and more ...

News Alert:
Steadicopter has completed the development of the first fully autonomous robotic helicopter.

NEW Flight Demonstration Video
Right click on link and choose "Save Target As ...".

Figure 14 – The Steadycopter robotic helicopter could be good candidate to fly test the concept of the tethered robot especially to demonstrate a tiny observation head stabilized by gravity.

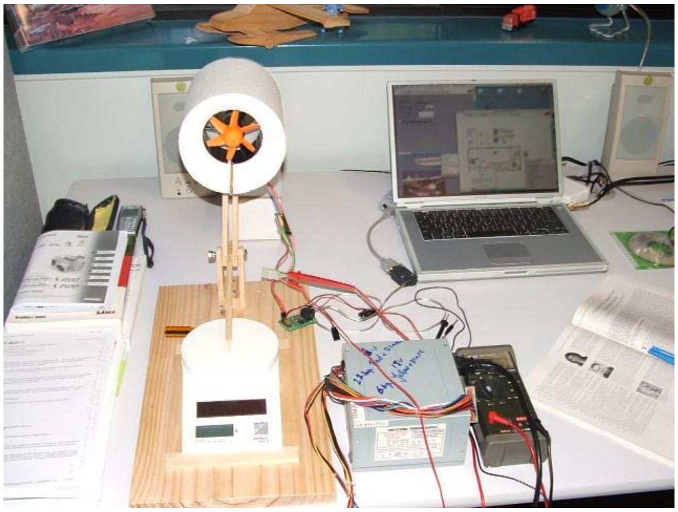


Figure 15 – Testing components for feasibility prototypes of the tethered robot or the agents. We use budget GWS ducted fan units, but also high quality carbon fiber units from Germany.

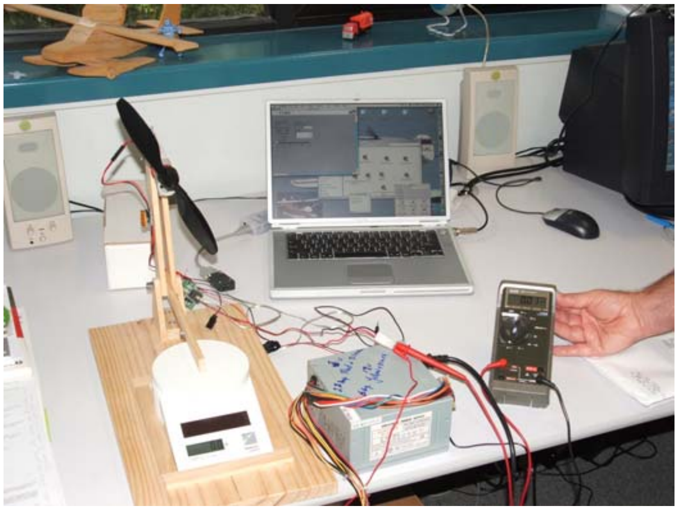


Figure 16 – Testing the thrust of a GWS gear motor unit with counter rotating propellers (the only kind we managed to find via Internet search).

The main challenge posted by the tethered robot (Fig. 4) is its control. The challenges are the ability to control the angular position of the yaw (the long line provides almost zero twisting torque), the angular position of the cable and the stabilization of the surveillance head attached to the robot.

We are also considering the possibility that the robot will be able to control its altitude by climbing on the cable rather than asking the platform to lift it or lower it to the ground. Adding the reel to the tethered robot can simplify the system especially for the coming tests (before using manned helicopter to test the system) since the host platform can be an anchoring point on a balloon or even a high rise building. Also, it could be a better altitude control by avoiding the delays of activating the remote reel on the host platform rather directly interaction with the reel's motor in the tethered robot.

For the new design we are currently testing a control system based on wireless Parallax environment for the tethered robot linked to LabVIEW virtual control panel running on the host laptop. Computer interface is based on Visa protocol over the USB port. We use extensively the Mini-SSC2 linked to GWS power controllers to run propulsion units.

In the past we conducted indoor and outdoor experiments with simple prototypes to access the quality of the video from the tiny wireless camera mounted on the custom made pan & tilt unit installed in the tethered robot. To control the motion we used a LabVIEW virtual control panel. To explore the effect of winds, we firstly used a strong indoor fan to represent the effect of the wind and later conducted outdoor experiments in a stormy day. We found that the very low frequency (the pendulum) of the tethered robot was not excited by the wind gusts. The concentrated weight of the batteries and low drag of the body combined with low drag of the long fishing line kept the system stable while the trees around were clearly wavering.

Figure 17 – We investigated the issues of controllability and computer interfaces using this setup. We tested hovering while being tethered to the lab ceiling and also as a free body.

Figure 18 – Testing the experimental setup in outdoor environment.

We are exploring the controllability of a gravity stabilised hovering system on an experimental setup. It also helps us in our effort in developing the computer interface and software.

7. FUTURE DESIGN

Our ideas and design approach is reflected from the following sequence of 3D CAD solid modelling prepared by Mr. Feri Acs.

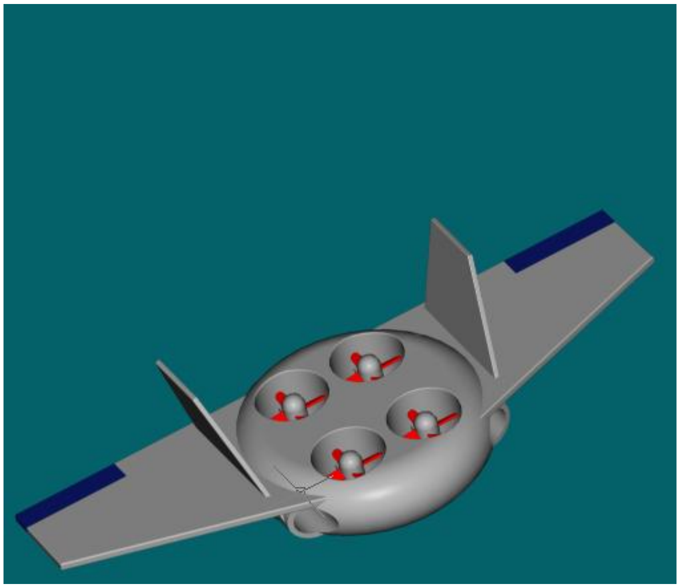


Figure 19 – CAD illustration for a short range flying-hovering platform.

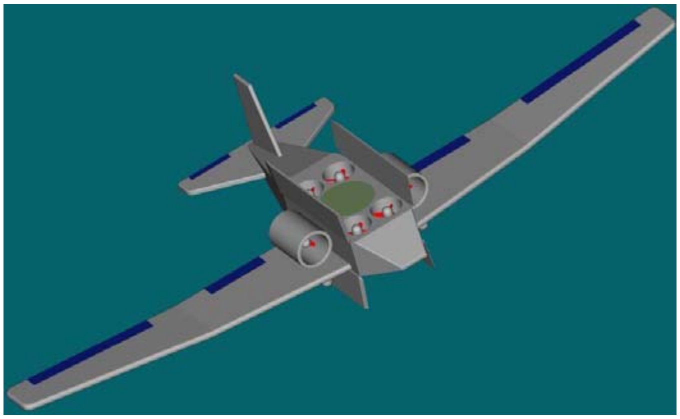


Figure 20 – CAD illustration for a long range flying-hovering platform in a hovering mode.

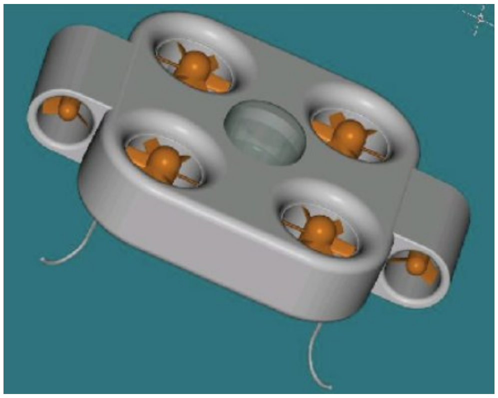


Figure 21 – Conceptual design of the agent based on four lifting ducted fan units plus two side by side smaller ducted fan units for forward motion and yaw control.

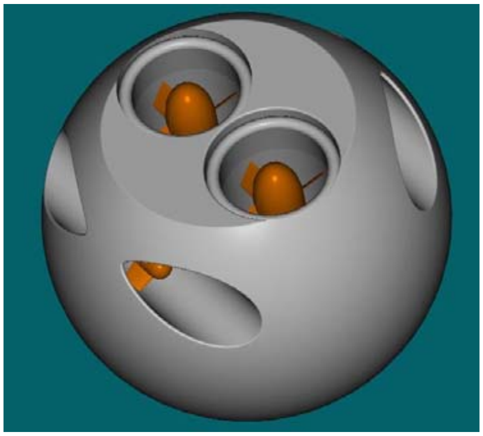


Figure 22 – Conceptual design of a spherical shape agent with two lifting ducted fan units plus side by side smaller ducted fan units for forward motion and yaw control.

Giving the agent a spherical shape (at least its lower part) and installing the heavy batteries (and much preferable also the electric motors for the lifting rotors) at the bottom gives them a Russian doll (known as "punch and stare") stability enabling them to land and take off from the rubble covering the floors after an earthquake or bomb blast. While sitting on the floor, they can turn off their propulsion units and observe the area to build a virtual navigation map, listen for signs of life and relay the collected data to the tethered robot. From there it would be relayed to the host platform and then onto the ground controller.

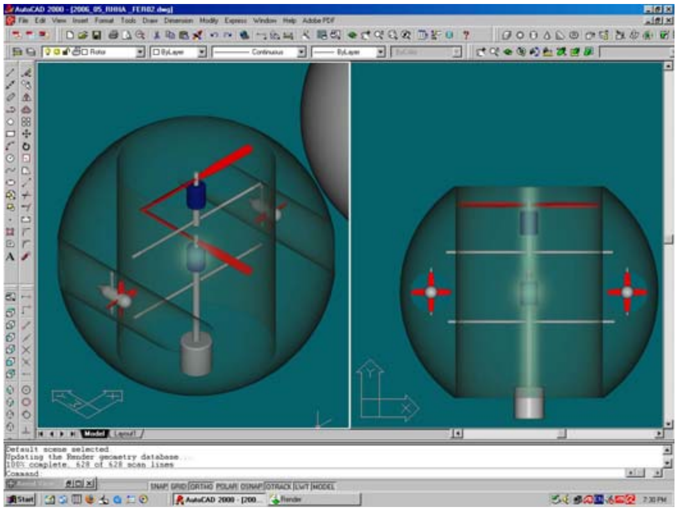


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Figure 23 – Conceptual design of the hovering-hopping agent based on lift generated by a counter-rotating coaxial pair of propellers and a counter-rotating smaller side by side pair for forward and turning motion. The location of the heavy battery at the bottom creates gravity stabilization in flying and a Russian dole behavior in take off and landing on rubbles.

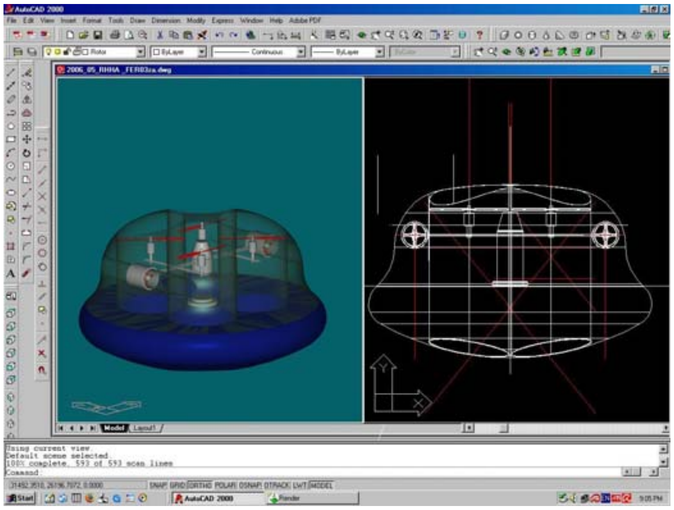

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Figure 24 – Conceptual design of the hovering-hopping agent based on lift generated by two pairs of counter-rotating propulsion units.

The agent can drag a power line to extend its range during the entrance phase to collapsed building. When the friction of the cable is beyond the agent's pulling capability, it can disconnect the cable and proceed on battery power. The motion of the agent - including landing and taking off while dragging a power line or free of the power line - presents serious challenges regarding control and stability.

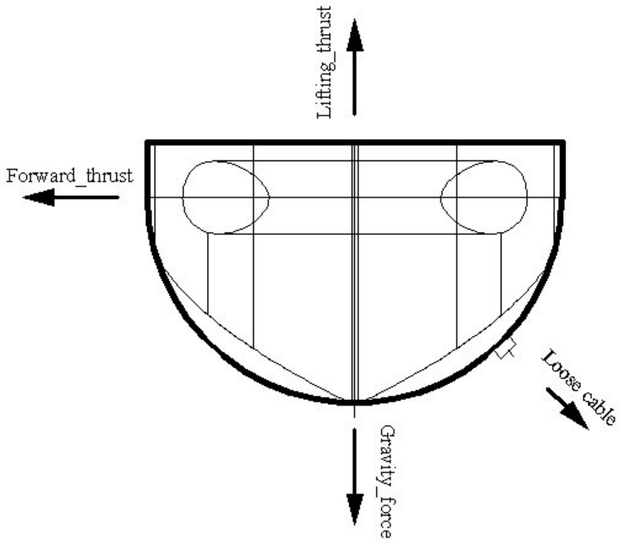


Figure 25 – Effect of pulling the umbilical cable during hovering.

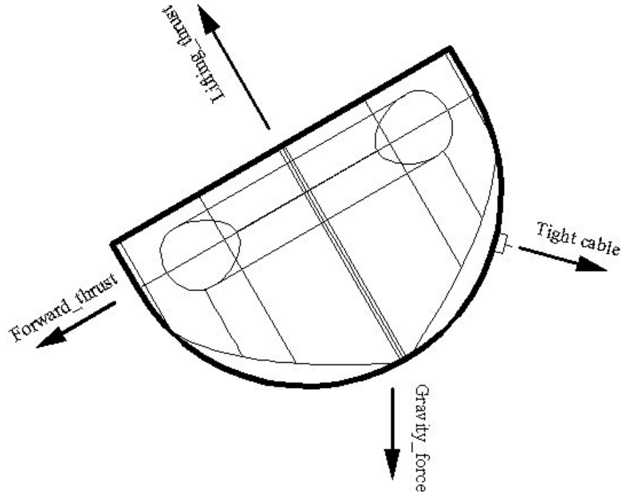


Figure 26 – Effect of pulling the umbilical cable during forward motion.

Our design for the agents is based on using ducted fan technologies and separation of functions to reduce the cross-coupling experienced in testing the DraganFlyer. We are adding a pair of counter rotating ducted fan units – much smaller compared to two or four lifting units - that directly control the yaw and forward motion. This change in design leaves the lifting units only one task so the propeller in the lifting units are accurately counter rotating and no gyroscopic aspects will effect the motion control of the agents.

The challenging problem of landing and taking off from surfaces covered by rubble may be solved by shaping the agents as a half-sphere with a very low centre of gravity. The agent should behave like a Russian doll that resists tipping over.

We used our past experience in analysis of damping aspects for gyro's systems nutations to explore the dynamics of the agents. The agent can be perceived as an inner gimbal system that floats in the air (instead of a set of gimbal system) thus the pitch and the roll torques are attached to it (the differential lifting forces). Pure hovering is considered to be a challenging operation but we hope to use gravity to achieve basic vertical stability mode by locating the centre of gravity (CG) at the lower end of the agent's body. One of the first questions to test is if the lower CG is enough to stabilize the agents or we need to apply the stabilization by installing an inertial navigation system (INS) similar to the approach taken in the DraganFlyer.

We plan to conduct the hovering experiments using INS unit developed by Peter Corke's group at CSIRO in Brisbane to record the angular orientations and rates during the hovering, landing and taking-off phases. Also concerning us are the transitions from hovering to landing and wise versa. The agents will need to proceed into the structure in small legs (resembling hopping) that includes longer sessions of quiet observation on the floor. The task of dragging the long power line and releasing it to proceed with battery power could be very challenging. Pulling the line will exert external forces which must be taken into consideration. The friction between the line and the floor plus its own weight will affect the balance of the agent. Locating the contact point at the bottom of the agent will tilt the agent so the lifting thrusters will help in pulling the cable (Fig. 26).

During observations of the targeted object, the data from the agent's sensor suit will be used to build a navigation map for the operators of the rescue operations. We plan to employ fuzzy logic algorithms to enable some level of autonomy especially needed for security operations. The agents will be provided with a navigation plan that is based on limited knowledge and will need to make local decisions by analysing the situation and thinking how to move forward to the goal.

We are currently developing control system based on wireless Parallax environment for the agent linked to LabVIEW virtual control panel running on the host laptop

8. CONTROL ISSUES OF THE FLYING PLAFORM

The host platform unmanned vehicle as we conceive it is a very challenging project [Fig. 20]. We perceive this aerial robot as a new generation of electric power aerial robotics. There are four lifting ducted fan units to provide the lift while two smaller ducted fan unit to provide the thrust forward. The electric power will be provided by an efficient turbo-generator optimised for low weight demand by using advanced neonyduim rare earth magnets plus air or liquid cooling for the generator construction. The propulsion configuration should provide good hovering stability plus good flying characteristic as a fixed wing mode. The classic design of helicopters with tail rotor is providing a balancing torque for main rotor but still accompanied by a lateral force which hinders hovering above a point on the ground. Balanced

The nearest exciting project is the unmanned version of the tilt rotor V-22 Osprey which is called Eagle Eye UAV made by Bell Helicopters. Such platform has the capabilities of shifting from horizontal flying mode to a hovering model. The second nearest platform could be the Fire Scout is unmanned helicopter made by Northrop Grumman. Both projects are being now assessed and hopefully will reach the production line. Currently it is a very expensive manned platform and the challenge will be to use the experience from this project and develop a budget robotic version. Our intuition says that this approach will be part of the trend of using robotics for difficult missions. It may be the future of the global UAV industry and currently we can mainly contribute to the conceptual analysis of such vehicles. It is beyond our current capabilities to deal with this vehicle but hopefully in future there will be other avenues of R&D cooperation that could advance this vehicle.

Another emerging technology that could be a candidate for the flying-hovering host platform is being developed by Urban Aeronautics in Israel. The X-Hawk employs ducted fan technology plus patented layers of van above and under the fans. The vans enable the vehicle to move to the sides (lateral motion control) and maneuver accurately (turn control). Currently the US navy is supporting feasibility research and the aim could be also an unmanned version which will be capable of carrying the tethered robot.

9. CONTROL ISSUES OF THE TETHERED ROBOT

The tethered robot is a double spherical pendulum (two pendulums connected). The mass of each pendulum can move on a conical envelope by changing the swing angle and the polar position of the cone base. The length of the cable is much longer compared to the distance between the hinge point of the robot and its centre of gravity. This proportion dictates a very slow main operation mode due to the cable accompanied by a relative fast mode of the rigid robot body. We developed a dynamic model and simulation in addition to testing a feasibility prototype. The gravity field helps to bring the tethered robot back to the vertical cable position, but the tethered robot is almost free regarding the yaw motion.

We plan to employ the same gyro technology used in model helicopters to stabilize the yaw. We will also explore the possibilities to use the propulsion units of the tethered robot to stabilize the swing angle if needed. We found by experiments in the lab (using strong fan) and outdoor (hanging a long dead weight is stormy weather) that the slow mode of the pendulum is not excited by wind gust. Still, there is a possibility that an active control will be needed due to platform movements.

Controlling the length of the cable is also an issue that needs attention. The length control could be done on the platform side or on the tethered robot side or concurrently on both sides. Attaching the drum to the platform seems to be logical since the platform has the ability to support the weight and the energy needs. On the other hand, integrating the drum with the tethered robot makes the system simpler as one unit that needs just to be hawked to any platform while using wireless communication with the tethered robot. A combination could be used: the course control by the platform but fine control of the robot above the ground by the tethered robot side.

The propulsion configuration of the tethered robot is another issue for the robot controllability. We tested two options. The first one employs a forward pulling unit plus a counter rotating units in the tail. The unit in the front is controlling the swing angle by pulling the robot from the vertical position of the cable. The two counter rotating unit in the tails control the polar position with minimum dynamic backlash. In this option there is more separation between yaw and pitch control.

The second option that we tested employs just side by side counter rotating units. This option looks more compact especially we you need to move close the structures or even into deep shafts. The two counter rotating units are responsible both to the swing position plus the angular position (yaw & pitch control). There is more cross coupling since the ducted fan units are designed only to generate thrust in one direction (design of the impellers and static vans is optimized to moving forward.).

10. CONTROL ISSUES OF THE AGENTS

The control issues for the agents are even more challenging in spite the fact that they are basically one mission robots. These tiny air vehicles have to take off from the launching pad located on the tethered robot and fly into confined and cluttered space of ruined houses. They need to negotiate their way between obstacles and survive collisions with walls and debris. To conduct quiet observation the robot needs to land on the rubble floor and turn off its motors. The landings and take offs also enable the robot to save its battery energy. We were considering the option to drag a power line in order to extend the agent range. Dragging the line could exert some difficulties on the motion control but may also help to stabilize the direction of the agent during its hopping mode.

11. SIMULINK DYNAMIC MODEL FOR THE AGENT CONTROL & NAVIGATION

Part of the research effort is to simulate the dynamic features of the hovering agent. We developed a Simulink model which takes into consideration all the gyroscopic couplings between the six thrusters and the gravity effects on the centre of gravity location. The model will be augmented in the future with control and navigation algorithms. The Simulink model provides modular structure with transparent links between the different functionality of each module.

The six thrusters are attached to the robot body making it easier to calculate the sum of the external forces and moments that act upon the robot body in a coordinate system attached to the robot's body. The vertical gravity field in the world system is transformed to the robot system, so during manoeuvres the observer attached to the robot will experience gravity in all three axes attached to the robot. Calculating the external forces acting the robot mass and the external moments acting on the robot inertia enables to find the three linear accelerations and three angular accelerations. Applying double integration enables to find the linear and angular velocities and distances in the robot system. To find the robot motion in the world system, the model detects the momentary increments in distance and transforms it to world increments. Summing all the world increments yields the robot motion in the world system.

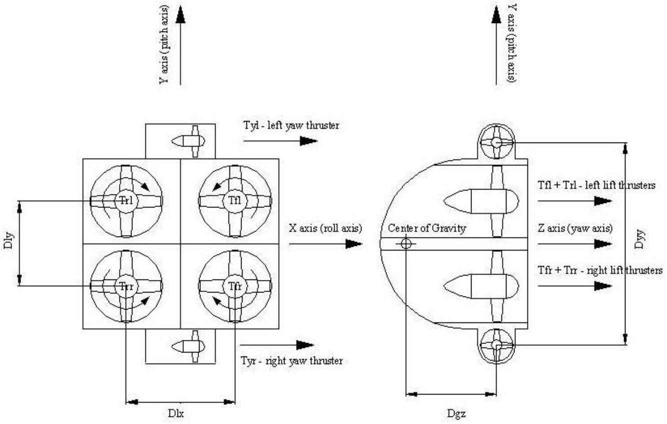


Figure 27 – Schematic depicting the parameters for the Simulink model.

To formalise the equation of motion, we selected the Newton-Euler approach based on formalising all the forces and moments compared to the energy based method of Lagrange which deals with the system degree of freedoms but leaves forces and moments hidden. The investigation used two classic text books [13] & [14]. Our case is simpler because all the thrusters are moving with the body of the robot compared to three gimbal systems (yaw, pitch & roll) where only the motor driving the inner gimbal is attached to the inner gimbal but the other motors are attached to the external gimbal and the roll gimbal. The agent model is expended from the two equations (eq. 1 & 2) of angular motion for two gimbal system with very small angular motions (eq. 5.64 & 5.64 in page 163 in [13]) into a full 3 axis DOF angular motion (eq. 4 & 5 & 6) and full 3 liner DOF motion (eq. 7 & 8 & 9):

$$J_y\ddot{\theta} + h\dot{\varphi} = M_b \tag{1}$$

$$J_Z\ddot{\varphi} - h\dot{\theta} = M_c \tag{2}$$

The 6 thrusters (the ducted fan units) are attached to the agent's body and moving with the agent's body. This is equivalent to the case of the torque motor which is attached to the inner gimbal - compared to the torque motor attached to the outer gimbal.

The transformation between the world system to the robot system are based on eq. 7-166 page 335 in [14].

The pseudo code behind the Simulink model (notations based on Figure 27):

```
% Tfr - front-right thruster
% Tfl - front-left thruster
% Trr - rear-right thruster
% Trl - rear-left thruster

% Tyr - yaw-right thruster
% Tyl - yaw-left thruster

% Dyx - propellers drag torque around X axis proportional to
angular
% momentum
% Dlz - propellers drag torque around Z axis proportional to
angular
% momentum

% Dyx = k1*Hy
% Dlz = k2*Hl

% k1 - drag torque coefficient from the yaw propellers around
X axis
% k2 - drag torque coefficient from the lift propellers around
Z axis

% Ttx - torque from thrusters around x axis 0.5*Dly*(Tfl +
Trl - Tfr -
% Trr) - k1*Hy
% Tty - torque from thrusters around y axis 0.5*Dlx*(Trl +
Trr - Tfl - Tfr)
% Ttz - torque from thrusters around z axis 0.5*Dyy*(Tyr -
Tyl) - k2*Hl

% Sfr - spin of front-right thruster
% Sfl - spin of front-left thruster
% Srr - spin of rear-right thruster
% Srl - spin of rear-left thruster

% Syr - spin of yaw-right thruster
% Syl - spin of yaw-left thruster

% Ifr - rotor inertia of front-right thruster
% Ifl - rotor inertia  of front-left thruster
% Irr - rotor inertia  of rear-right thruster
% Irl - rotor inertia  of rear-left thruster
```

% Hl - total lift spin momentum (Sfr*Ipfr + Sfl*Ipfl + Srr*Iprr + Srl*Iprl)

% Hy - total yaw spin momentum (Syr*Ipyr + Syl*Ipyl)

% Gfx - x component of gravity force
% Gfy - y component of gravity force
% Gfz - z component of gravity force

% Tgx - torque from gravity around x axis Gfy*Dgz
% Tgy - torque from gravity around y axis -Gfx*Dgz

% Jx - body inertia around x axis
% Jy - body inertia around y axis
% Jz - body inertia around z axis

% Mr - robot's mass

% x - x axis is the roll axis of the agent
% y - y axis is the pitch axis of the agent
% z - z axis is the yaw axis of the agent

% X - X axis of the world system
% Y - Y axis of the world system
% Z - Z axis of the world system

% world system [XYZ] to agent system [x y z] is achieved by Euler transformation
% reference textbook - Donald Greenwood "Principles f Dynamics"
% See also AgentTransformationMatrix1.m

% rotate Psi around Z
% rotate Teta around y'
% rotate Omega around x"

% PsiDot is the angular rate around Z
% TetaDot is the angular rate around y
% OmegaDot is the angular rate around x

% PsiDotDot is the angular acceleration around Z
% TetaDotDot is the angular acceleration around y
% OmegaDotDot is the angular acceleration around x

% [x y z] = [Euler transformation]*[X Y Z]

% Dgz - distance along the z axis between centre of gravity and aerodynamic
% centre (cross of lift thrusters and yaw thrusters)

% Dlx - distance along the x axis between the front and rear pair of lifting thrusters

% Dly - distance along the y axis between the right and left pairs of lifting thrusters

% Dyy - distance along the y axis between the right and left of the yaw thrusters

% Tox - total external torque (thrusters & gravity effects) around x axis Ttx + Tgx
% Toy - total external torque (thrusters & gravity effects) around y axis Tty + Tgy
% Toz - total external (thrusters & gravity effects) torque around z axis Ttz

% Tox = Ttx + Tgx = 0.5*Dly*(Tfl + Trl - Tfr - Trr) + Gfy*Dgz
% Toy = 0.5*Dlx*(Trl + Trr - Tfl - Tfr) - Gfx*Dgz + xDotDot*Mr*Dgz
% Toz = Ttz = 0.5*Dyy*(Tyr - Tyl)

% The equation of motion presented in GyroDynamics book by Arnold and Mounder page 160
% (in the book the x axis is the spin axis - and not the z axis as in our agent model for the 4 lifting units):

% Jy*TetaDotDot + Hl*PsiDot = Toy

% Jz*PsiDotDot - Hl*TetaDot = Toz

% Jx*OmegaDotDot = Tox

% the equation of motion for the robotic agent (the 3 angular degrees of freedom):

% Jx*OmegaDotDot + Hl*TetaDot = Tox (4)

% Jy*TetaDotDot - Hl*OmegaDot + HyPsiDot = Toy (5)

% Jz*PsiDotDot - Hy*TetaDot = Toz (6)

% the equation of motion for the robotic agent (the 3 linear degrees of freedom):

% Mr*xDotDot = Tyr + Tyl + Gfx (7)

% Mr*yDotDot = Gfy (8)

% Mr*zDotDot = Tfr + Tfl + Trr + Trl + Gfz (9)

XII. MODULARITY OF SIMULINK MODEL

The Simulink model is based on six user defined S-Functions (user defined function compared to library functions):

1. Sum of all external forces acting on upon the robot’s mass.

2. Sum of all external moments acting on the robot's inertias.
3. Transforming the gravity field from the world system to the robot system.
4. Control of the six thrusters.
5. Transforming the linear increments in the robot system to the world system and summing the accumulated distances.
6. Animation for motion of the robot system with respect to the world system.

The model is built around six integration channels: 3 channels of linear motion and 3 channels of angular motion.

In the future we plan to add new modules for the sensor suit and module for the navigation planner which will include fuzzy logic algorithms.

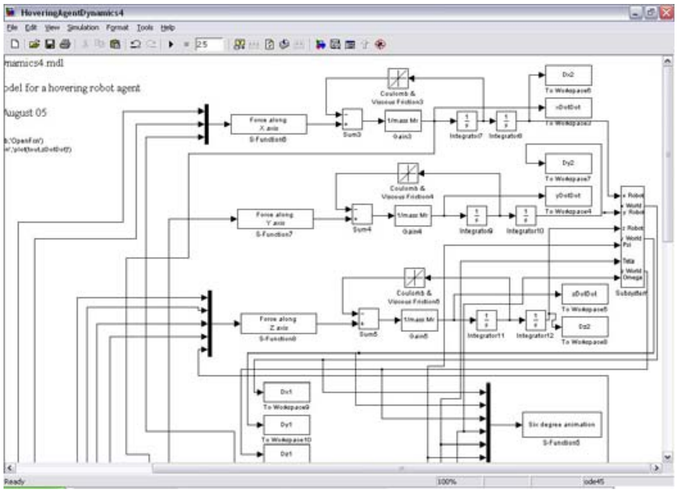


Figure 28 – The three linear motion integration channels

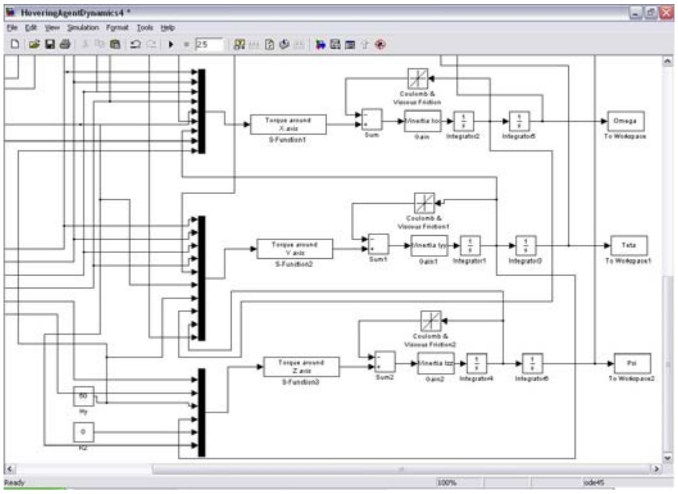


Figure 29 – The three angular motion integration channels

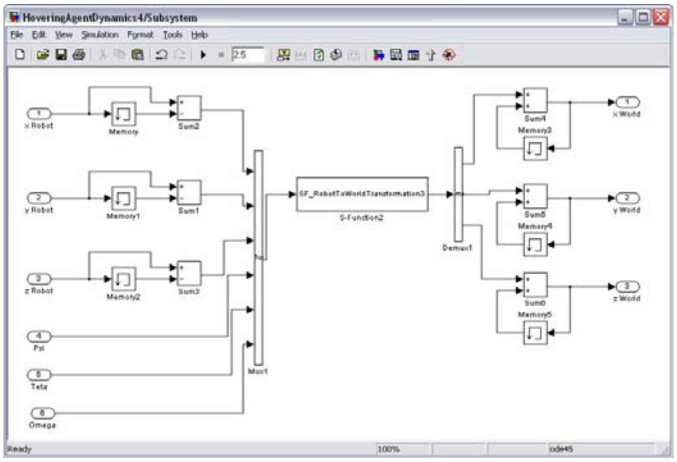


Figure 30 – The transformation of the linear increments from the robot system to the world system and accumulating the distances in the world system

12. MAIN FEATURES OF THE DYNAMIC MODEL

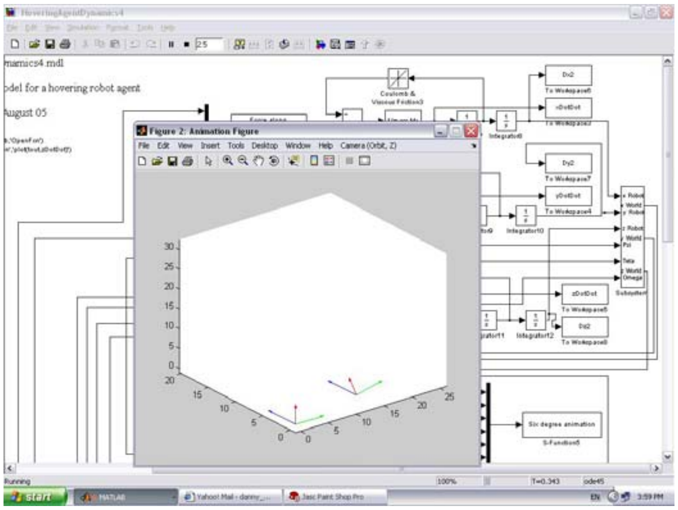


Figure 31 – The robot's system is moving with respect to the world system

The following figures depict a few results from the simulations. The model enable us to explore features of the agent's dynamics including cross-coupling due to the existence of six spinning propellers, the issue of nutation oscillations and the issue of gravity stabilisation.

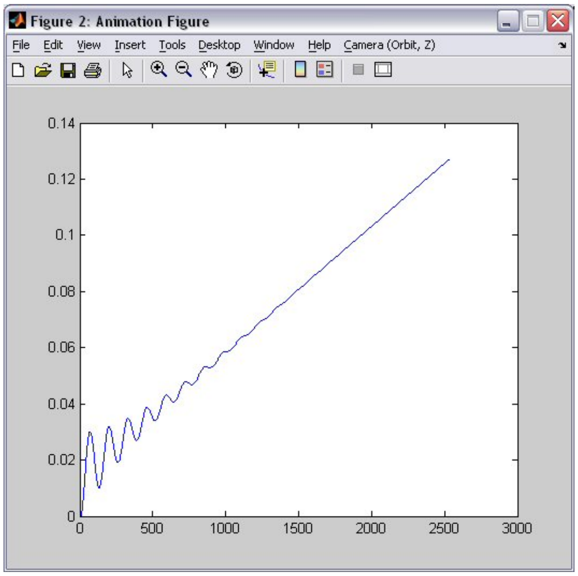
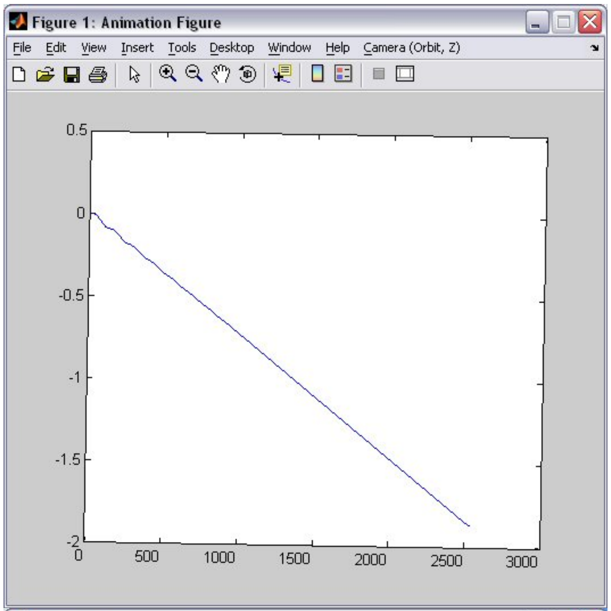
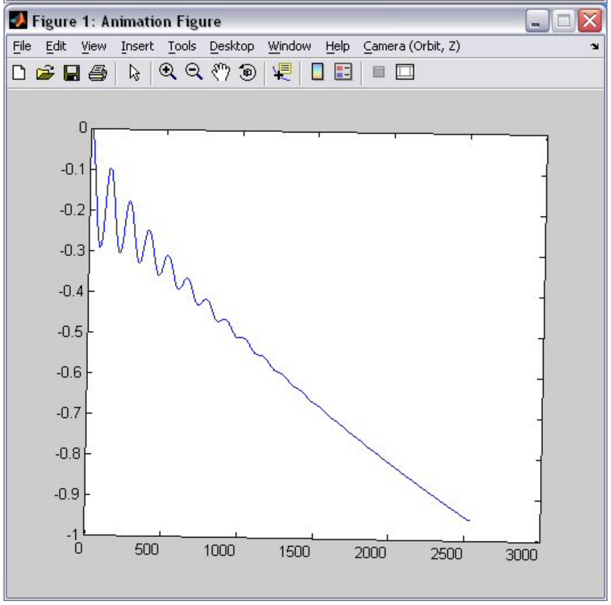


Figure 32a 32b 32c – 32a is a plot of Psi showing damped nutations caused by unbalanced angular momentum of the yaw thrusters (Psi is the yaw angle around z the vertical axis of the robot). 32b shows behavior of Teta (pitch around y axis of robot). 32c shows the behavior of yDotDot (linear acceleration along y axis of robot built by gravity component during roll).





13. CONCLUSIONS

We are the middle of intensive effort of model simulating and prototypes testing of the system's components. The impression so far indicates that the conceptual ideas have a great potential to give solutions to challenging needs in the future of robotics applications for rescue and security operations.

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REFERENCES

[1] D. Greer, P.J. M^{c}Kerrow, and J. Abrantes, 2002. 'Robots in Urban Search and Rescue Operations', Proceedings ACRA'2002, Aukland, November, pp 25-30.

[2] R. Murphy, et.al., Mobility and sensing demands in USAR, IECON'02, V1, pp138-142, 2000.

[3] Ratner D. and McKerrow, P.J.,2002, DSTO 2002 'Sky-Eye robotic air-ship with tethered self-manoeuvring sensing aerial pod for law enforcement', Defence Science Technology Organization (DSTO) Edinburgh South Australia. Poster presentation and seminar proceedings CD, 23-24 May 2002.

[4] Ratner D. and McKerrow, P.J., SPIE 2004,. ' Using tethered robotics to launch flying and hovering robot agents for tactical air-superiority in land warfare and anti-terrorist activities', Proceedings volume 5409 , pp 39-49, Orlando USA, April 2004.

[5] V-22 Osprey Tilt-Rotor aircrfat - http://www.boeing.com/rotorcraft/military/v22/flash.html

[6] X-Hawk aerial vehicle - http://urbanaero.com/Frame-X-Hawk.htm

[7] DraganFlyer - http://www.rctoys.com/draganflyer3.php

[8] J.Seddon, Basic Helicopter Aerodynamics, American Institute of Aeronautics and Astronautics, 1990.

[9] H. J. Kim, D. H. Shim and S.S. Sastry : Flying Robots: Modeling, Control and Decision Making. ICRA 2002, 66-71.

[10] D.H. Shim, H.J. Kim, H. Chung and S.S. Sastry, Nonlinear model predictive tracking control for rotorcraft-based unmanned aerial vehicles. American Control Conference, Alaska, May 2002.

[11] Mike Rogers,'VTOL Military Research Aircraft', Orion Books NY 1989.

[12] McKerrow,'Modelling the DraganFlyer four rotor helicopter', Proceedings IEEE ICRA New-Orleans USA April 2004 pp 3596-3601

[13] Gyrodynamics by Arnold and Mounder

[14] Principles of Dynamics by Donald Greenwood

[15] Eric Thouvenin, 'Modelling Twin Coaxial Rotor Helicopter', MSc research thesis, supervised by Phillip McKerrow and Greenoble University France