

Conceptual Hybrid Micro Aerial Vehicle with Vector Thrust and Automatic Target Recognition System for both Indoor and Outdoor Operation

C.-M. Kuo¹⁾, C.-H Kuo¹⁾ and C. Boller^{1,2)}

¹⁾Natural Science Faculty III, Saarland University, Saarbrücken/Germany

²⁾Fraunhofer Inst. for NDT (IZFP), Saarbrücken/Germany

Micro aerial vehicles (MAV) are considered to operate in an urban environment, where flyable space is limited and maneuverability is required. In excess indoor operation might be required too for an inspection mission which is difficult to be achieved with a fixed wing MAV due to the higher speed when compared to a rotary wing MAV. However the fixed wing operation may become a must if the indoor target is sufficiently far away and endurance becomes an issue. Furthermore stability of an image taken may not be promoted by vibrations caused from a rotary wing MAV. To solve the problem as well as enhancing an MAV's performance in urban missions, a conceptual hybrid micro vehicle has been created. Using a system of systems and modular design approach, a bio-inspired ground vehicle with rotary "legs" has been designed. This vehicle is able to walk on a variety of different terrains, cross obstacles and operate and able to communicate same ground station with MAV flying around. The ground vehicle and the MAV both share the same type of autopilot, camera system, fuselage and possibly others. The MAV has been further equipped with the walking features of the ground vehicle and a 2DOF vector thrust option for super-maneuverability in the air and ground jump take off capability, hence creating a hybrid vehicle. Based on a color pattern, a low weight and cost target recognition system has been designed and realized using off-the-shelf components. This has been done in combination with a laser range finder which detect the distance from target and automatically adjust the parameters for target recognition allowing workload of the operator during an indoor inspection mission to be decreased. Each of the systems, ground as well as aerial, has been validated in experimentation, first in a single mode of each system and then in a combined mode including the 2DOF vector thrust propulsion system being installed on the fixed wing MAV. Some of the progress achieved in that regard will be provided within the presentation.

Introduction

Micro aerial vehicles are, by definition, small aircraft which fly at relatively low speeds (usually less than 30 mph). Because of this combination of flight characteristics, MAV flight is said to be associated with low Reynolds numbers (less than 200,000).

MAV are in this project has wing span of 40cm and flight speed of 6m/s, which are very similar to small size bird such as pigeon, therefore, bio-inspired concept can be design and released on the platform.

From biological point, bird located their target from air, then either dive to attack on target or land on the ground, and move closer to target (by leg) for detail analysis. Once analysis is finished, it can be taken off again with in very short run way distance.

Such feature are desired for micro air vehicles, as the payload is very low, most of time only low resolution camera can be carried, therefore for closer inspection of the target site in confirm space is not possible with fix wing MAV. For the rotor wing MAV, endurance is biggest factor for such mission, therefore, in order to satisfy aerial video and close range inspection, a combination of function from ground vehicle and air vehicle must be designed (ie, similar to bird).

Challenges

Most of ground vehicles are using either wheel or track as for moving around on ground. Even though, wheel can be design in a very light weight fashion (which is very common in hobby field), but its efficient on the rough terrain is not very high.

On the other hand, track type ground vehicles have good efficient on different terrain, however, the mechanism is base on the weight of the vehicle, which means most of time, track vehicles are heavy weight.

Since MAV has very limited payload capacity (including space capacity), either track or wheel is not be able to apply on the MAV, a new type design in combination of light weight but also able to move though rough terrain is required.

Rotating leg design

In nature, birds and insect all uses legs for ground movement, which are able to cope with rough terrain and flat ground. Each of the leg has at least two joint allow to adapt and moving though different surfaces, and control of these joint and movement is rather complex that will not be able to implement on to MAV autopilot.

Mathematical and control method for rotating wheel are well established for centries, therefore, the concept of rotating wheel and leg must be mix together.

Using modular MAV as platform [1], leg size should be no larger than fuselage, and should not interference with airflow too much, hence as thin as possible and length in no greater than 12 cm in Y axis (global coordinate, see Fig. 1).

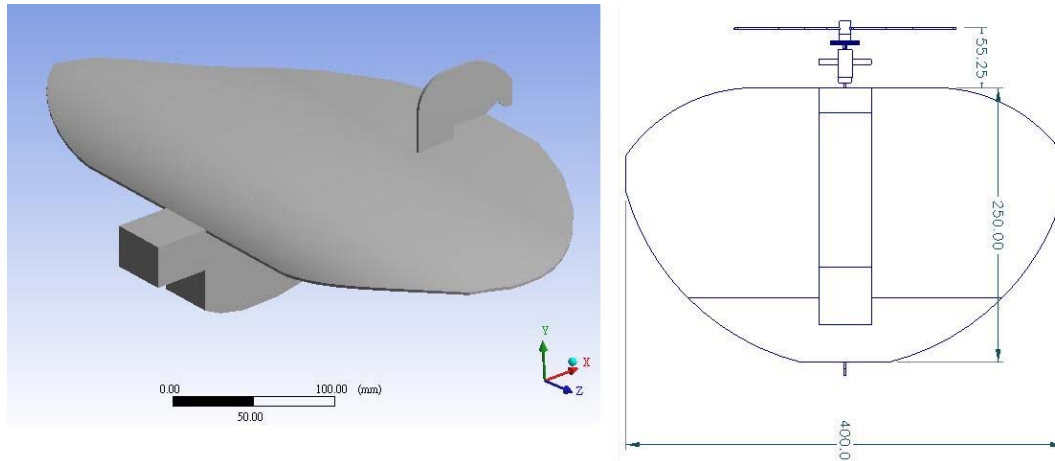


Fig. 1. Left, platform MAV with global axis. Right, the platform MAV with dimension drawing.

The best material option for such rotating leg is carbon fiber composite as it is light weight and able to create damping for MAV under shock loading in the ground or during landing. However, put cost and manufacturing, ABS plastic is more reasonable, hence will be selected as base material in the design stage.

The first design of the rotating leg can be seen in Fig. 2, the leg has very thin four ligament for supporting weight and creating enough contact surfaces (friction) to the terrain.

Optimization of the rotating leg

The first design of leg is simple, because it has the sharp angle that will create singularity in the Finite element simulation, therefore a more sensible design will be using the “curve” instead of sharp edge (Fig. 3)

The optimization of the leg consider both static and dynamic loading, and parameters are the thickness and radius of curvature for the ligament (see Fig. 4).

$$X = \begin{Bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \end{Bmatrix} = \begin{Bmatrix} V_1 \\ V_2 \\ H_4 \\ H_5 \\ Thickness \end{Bmatrix} \quad (\text{see Fig. 4}) \quad (1.1)$$

For the static case, loading is consider as weight; for dynamic, assume the worse impact case is when MAV is during fast landing, therefore, initial speed for FE model will be its flight speed (8m/s).

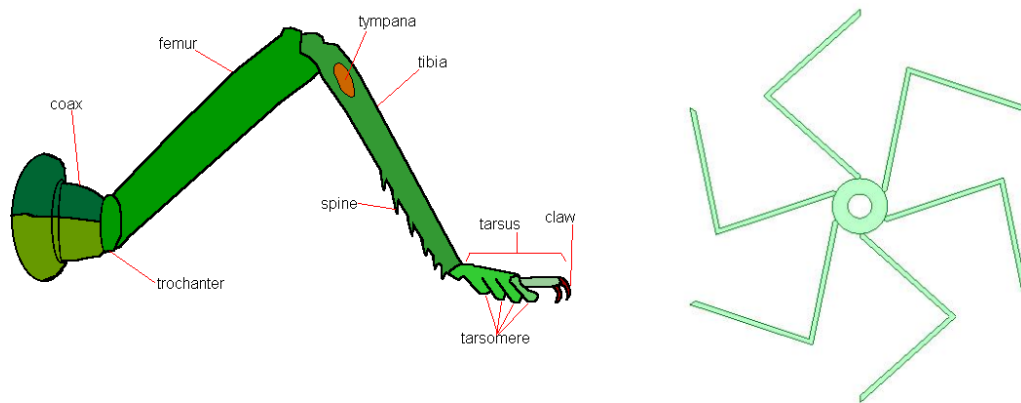


Fig. 2. Left, insect leg. Right, bio inspired “rotating leg”

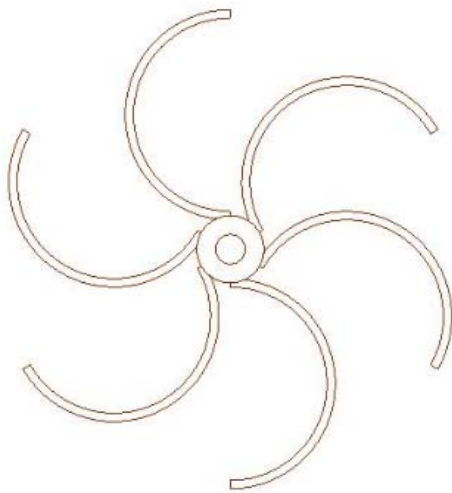


Fig. 3. modified the leg, without any sharp edge.

Since the dynamic simulation is base on the energy of the impact, and our FE model is only section of “leg”, therefore, an energy match equation was used to mach up the impact energy, hence the impact velocity is set at 30m/s.

$$1/2m_1v_1^2 = 1/2m_2v_2^2 \quad (1.2)$$

Both static and dynamic simulated results of “leg” are shown in Fig. 5. Top left and right shows the static results (left is the stress pattern, right is the deformation), bottom left and right shows the results of dynamic impact (left is the deformation, right is the stress pattern)

Output parameters are the deformation, stress level and the overall volume of the leg structure (minimum stress level and volume is the optimized point). With these parameters, numbers of random sample are generated and calculated, then optimization is by using genetic algorithm to go though all the sample, few equations

are generated to search the optimized model [2], [3]. The optimized model has only 43% of the original volume but same strength.

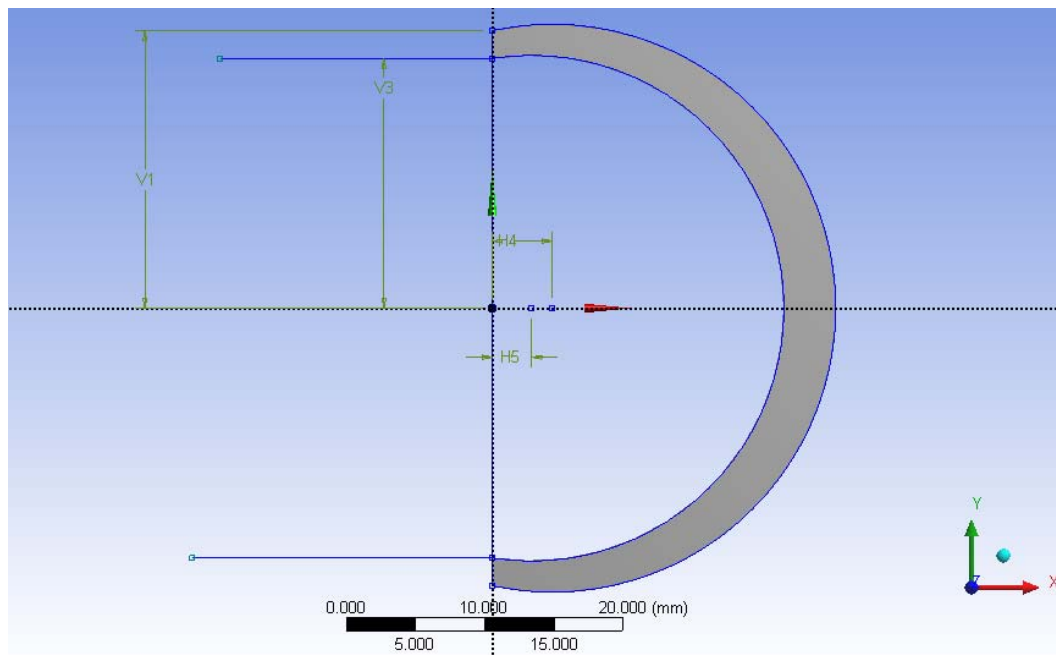


Fig. 4. the section of the rotating leg. Note: V1, V3, H4 and H5 are the parameters for the size of leg, curvature and thickness of the leg.

$$\begin{aligned}
 &19 \leq V_1 \leq 22.015 \\
 &16 \leq V_2 \leq 18.3 \\
 \text{Condition } &3.8 \leq H_4 \leq 4.8 \quad \text{output } \min \left\{ \begin{array}{l} \text{Deformation}(Y) \\ \text{Stress} \\ \text{Vulume} \end{array} \right\} \\
 &2.5 \leq H_5 \leq 3.1 \\
 &3 \leq \text{Thickness} \leq 5
 \end{aligned}$$

Parameter	V1 (mm)	V3 (mm)	H4 (mm)	H5 (mm)	Thickness (mm)	Overall volume %
Original design	20	18	4.32	2.83	4	100
Optimized design	19.142	18.044	4.0149	3.0372	3.0041	43

Table 1. Parameter comparison of the original and optimized model.

Since the autopilot from the group is able to produce PWM signals to control standard servos, therefore power drive for rotating leg are also using servos.

Standard servos are modified both mechanically and electronically to allow 360 degree continually rotating[4].

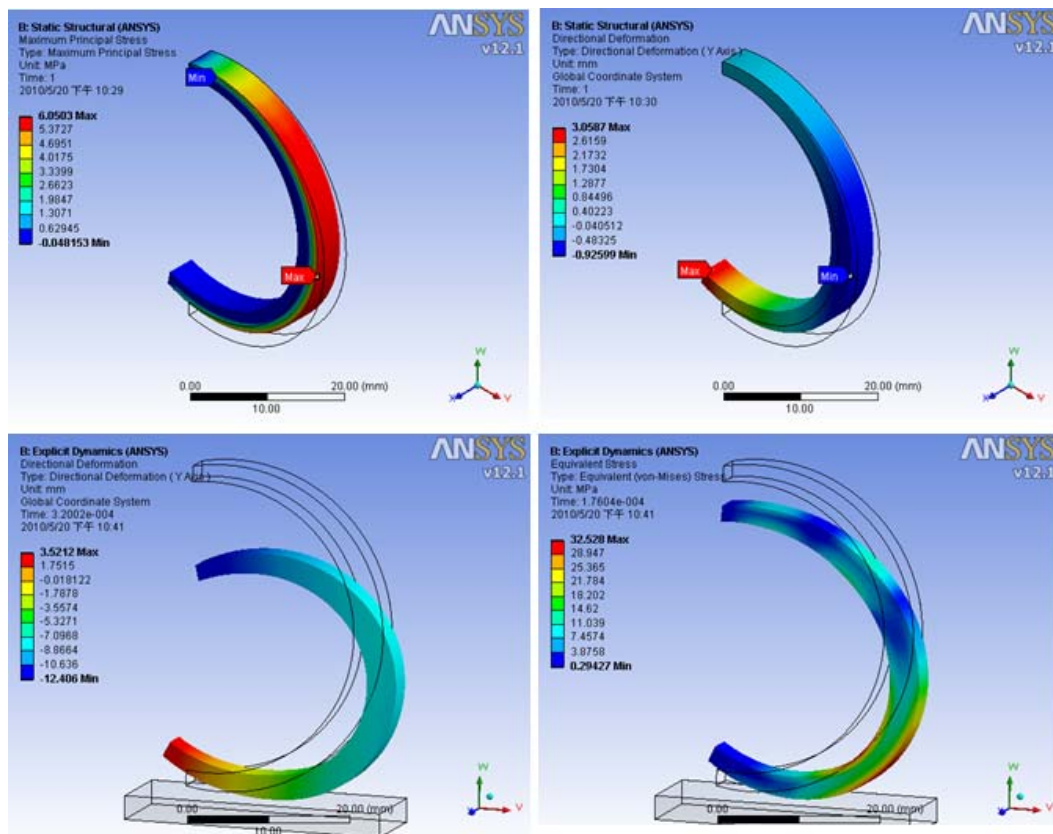


Fig. 5. Both static and dynamic simulation results of the “leg”

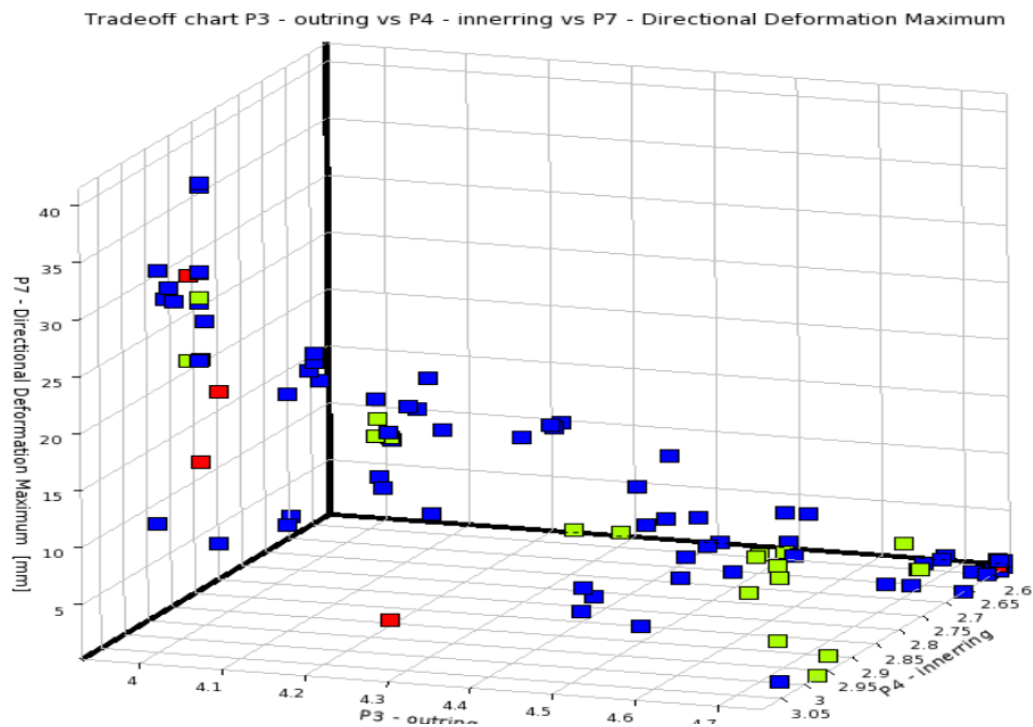


Fig. 6. The trade off study graph from the optimization process

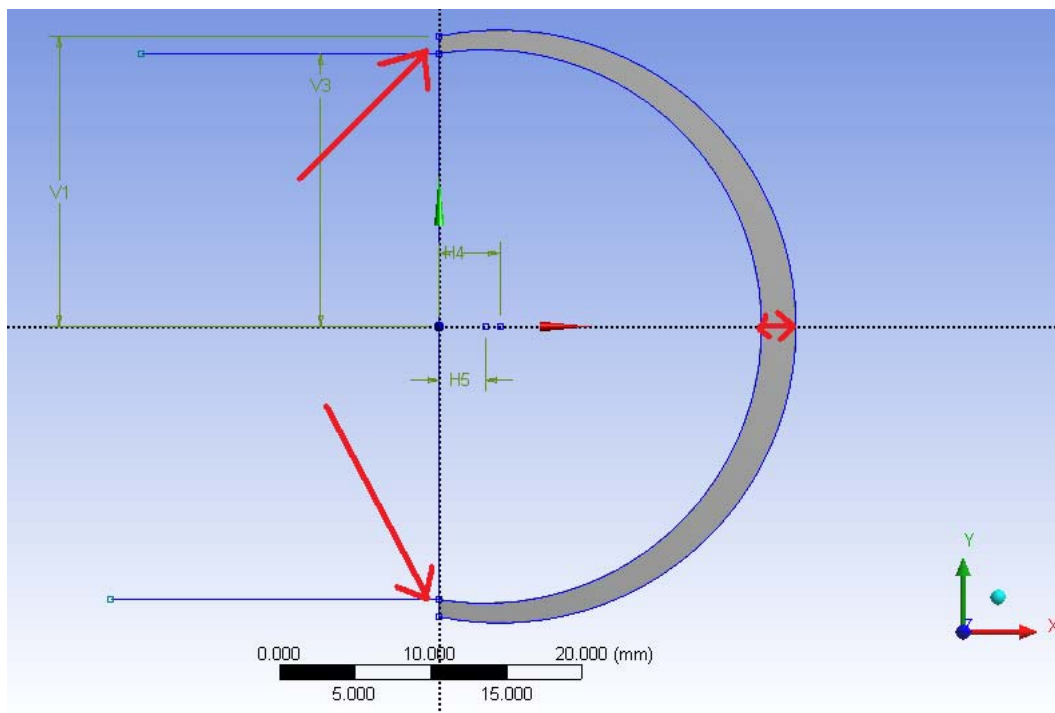


Fig. 7. Optimized leg. Note: the red arrow indicate the modified area.

Rotating leg in hardware

The manufacturing of optimized leg is rather difficult as either injection mold or



Fig. 8. Left, the "leg". Right, un-modified the light weight wheel. Note: each side of the ruler indicates 15cm.

Prototype Remote control Ground Vehicle

The flight control code are modified to allow the control of rotating leg, and the testing ground vehicle with rotating leg are design to validate the design of software and hardware.

The system integrate one axis digital compass to allow the Remote Ground Vehicle to identify its heading during stationary and indoor environment. At current stage, the RGV are able to navigate outdoor with GPS, and indoor operation are totally remote control though Ground Control Station (GCS). Since it share the same autopilot system and communication protocol, therefore, one GCS allow to control multiple vehicles (ie standard MAV with RGV at same time or two RGV at same time)

Series experiments were carried out for testing capabilities of the rotating leg in both outdoor and indoor terrain with rough surfaces.

The experiment shows the single maximum obstacle that rotating leg could climb though is relate to the spaces between ligament, and in this case is 6 cm, which is enough for most of indoor operation and certain outdoor missions.

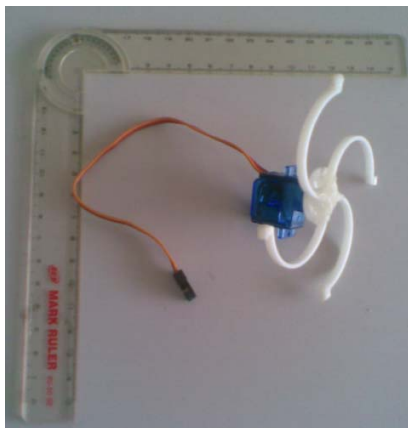


Fig. 9. installation of the rotating leg to the modified servo. Note: each side of the ruler indicates 15cm.

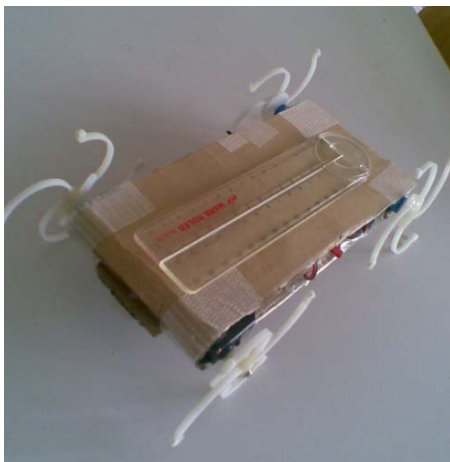


Fig. 10. RGV prototype, note: the ruler in the photo is 15cm ruler.

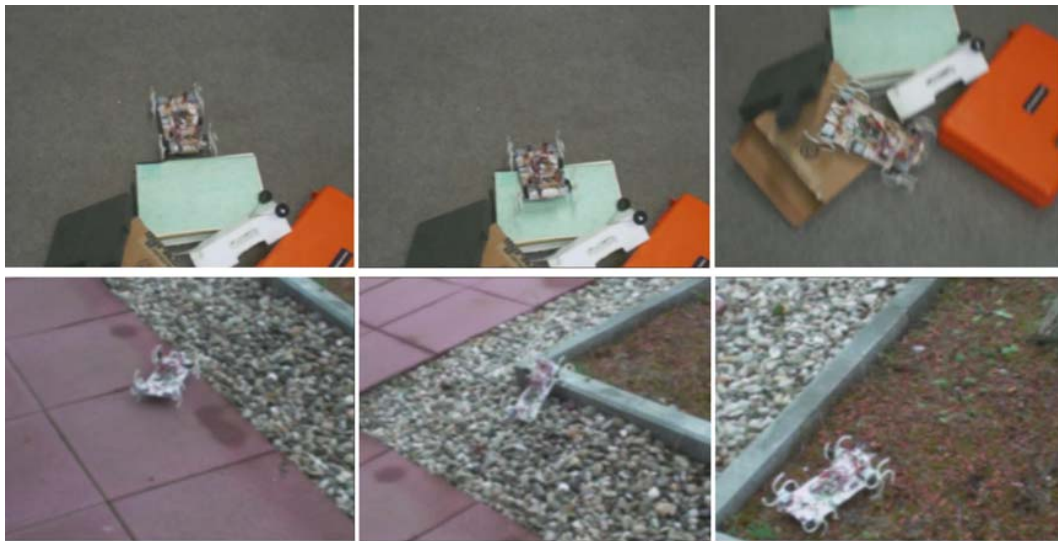


Fig. 11. Top, RGV during indoor testing. Bottom, RGV in outdoor environment.



Fig. 12. Ligament space of the rotating legs

Shock and drop tests were carried out for testing if the autopilot and ligament were able to survive from hard landing and drop from sky. Results were very positive, the RGV has been tested to go from 2nd floor though stair to ground floor without any damage (because of the ligament providing shock resistance like spring and damper).

Since different size off-the-shelf “rotating leg” are available, therefore, the group had later constructed a smaller version of the RGV which only weight 125g (xx % weight drop) and 4.5 cm long. The over strength are similar, and same shock tests were carried out to test its survivability.

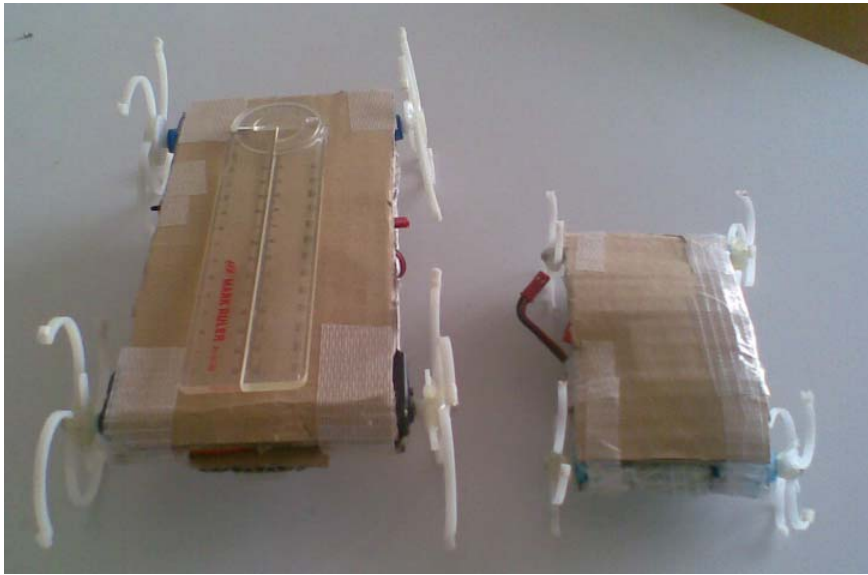


Fig. 13. Left, RGV. Right, the small RGV (equip the same autopilot system)

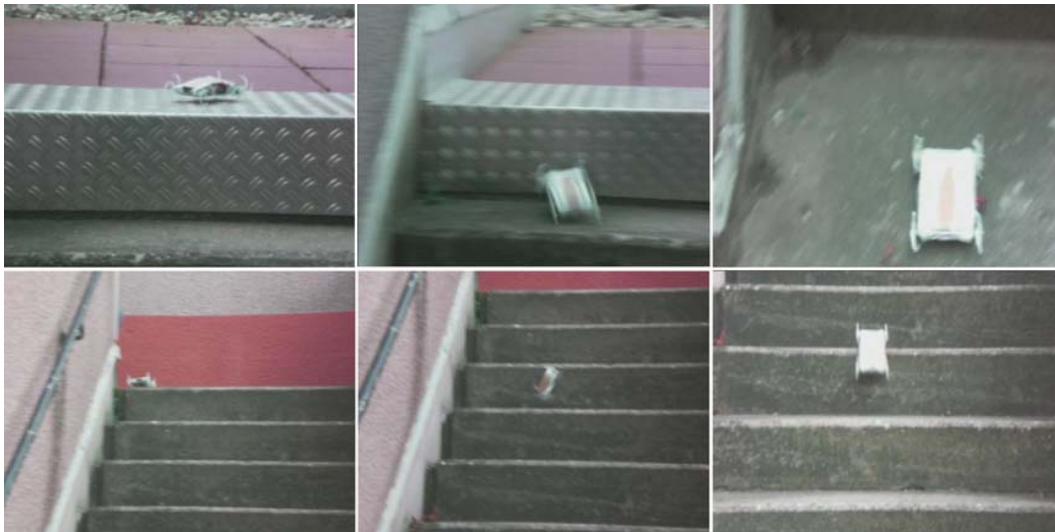


Fig. 14. Little RGV drop tests. Note: RGV survive the shock tests for more than 20 times.

Platform MAV

The platform MAV has 1 DOF vector thrust[5], which was able to produce very good maneuverability for lateral motion and boost up the overall endurance. However, the requirement for hybrid vehicle is it have to be able to jump from ground (take off with and assistance), and for this case, lateral direction vector thrust is not suitable, hence, 2 DOF vector thrust mechanism is designed.

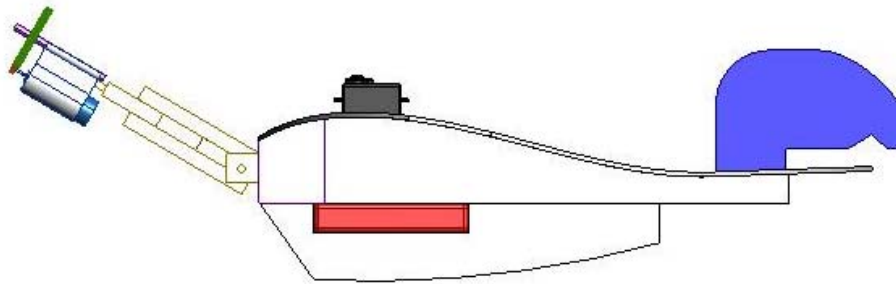


Fig. 15. CAD model of 2 axis vector thrust MAV for converting to hybrid vehicle

2 DOF vector thrust require re-build the mathematical model for flight control, which is rather difficult, therefore, the thrust rotating in Z axis (global coordinate system) is only use during take off stage.

Due to physical space limitation, the rotation angle for thrust is limited to max 50 degree only, and with maximum thrust condition, the upward thrust is 1.85 Newton (at max) [1]

Optimization of the rotating angle for minimum take-off distance

Theoretically, the larger the rotational angel for thrust will generate larger upward forces, which should lower down the take off distance. However, in reality is not so simple due to aerodynamic of the fix wing MAV. In order to determine the effect of the angle of the thrust and take off distance, series of Computational Fluid Dynamic model of the hybrid vehicle are generated.

Since the MAV geometry is complex, the use of K ω model become difficult and required high computational resources in storing the detail of boundary layer mesh. The average element within the simulation is about 2.2 million cells, and flow region is more than 12.5 times of the chord length.

This simulation set up has been validated in wind tunnel in [6],[7], and results are fit with 5% error range.

The wing of the MAV is assume to be rigid (extra support has been installed), therefore the effect of the aeroelasticities are ignored.

Thrust angle and ground speed are the parameters for the CFD simulation, the results are shown in Fig. 17

From both physical law and results, it can very easy to see that with higher angle of thrust, less ground velocity is needed for taking off the MAV, however, the velocity is not representative for the take off distances.

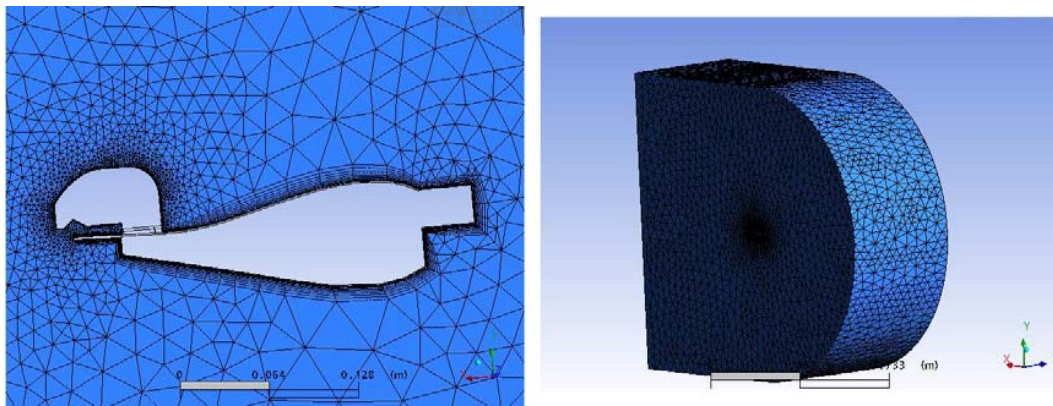


Fig. 16. CFD mesh of the MAV. Left shows the detail of boundary layer mesh. Right, the overall flow field mesh.

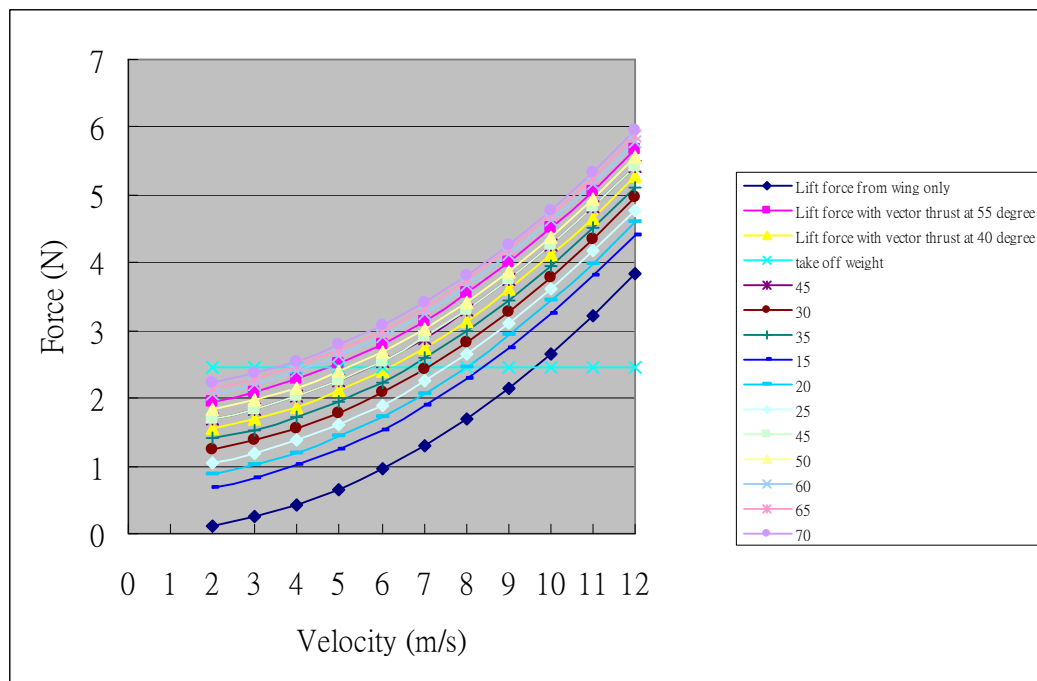


Fig. 17. Lift against the different velocity for different thrust angle setting

One of the factor did not considered in the CFD simulation is the ground friction and acceleration cause by the thrust in X direction. The value of friction force are estimated by both material properties of the ground and FE simulation.

By using combination of different forces acting on MAV before take off, the take off distance can be estimated by eq (1.3) [8]

$$S = \frac{V^2}{2 * ((T_x - D_x - D_g) / m_1)} \quad (1.3)$$

CFD and FE results, the take off distance of the hybrid vehicle against different angle for vector thrust is shown in Fig. 18

The result in Fig. 18 indicate that take of distance is at minimum when the thrust angle is at 55 degree and take off distance is at around 3.5 meters.

With these information, the real prototype of hybrid vehicle can be constructed very rapidly.

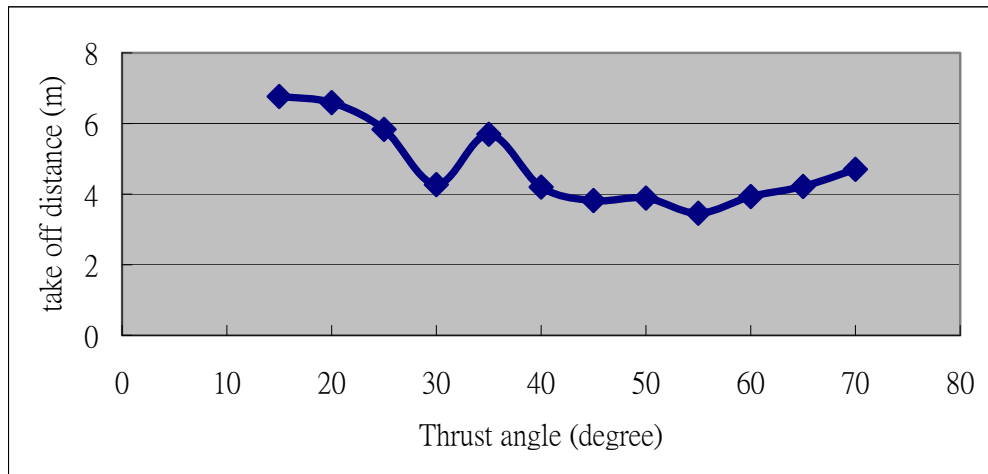


Fig. 18. Take of distance against different thrust angle setting

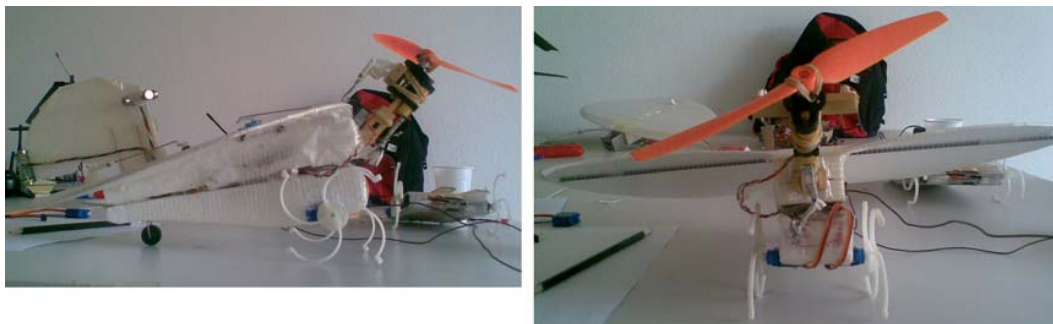


Fig. 19. Left, side view of the hybrid vehicle. Right, the front view of the hybrid vehicle. Note the thrust angle and rotating leg.

Flight stability analysis

Platform MAV are proved have a good stability and controllability during the steady flight condition, however, for the hybrid vehicle, analysis of the take off stability is required, as with setting for minimum take-off distance may not have enough stability to allow the MAV to lift off ground. Analysis method can be found in [9],[10],[11],[12].

Longitudinal stability

The results from shows the damping ratio decrease as the angle of thrust increase,

and this is caused by the shift of CG position in X-axis (the body frame system) on the overall vehicle. For the optimized take off distance, the MAV is shown as not stable longitudinally. Looking at the angle of 45 degree, the results shows the MAV is at neutral position (not stable, but not unstable) and take off distance from Fig. 18, the take off distance is 3.8 meters, which is slightly higher than the optimal distance, but it can form a good experiment point to test the actual hardware.

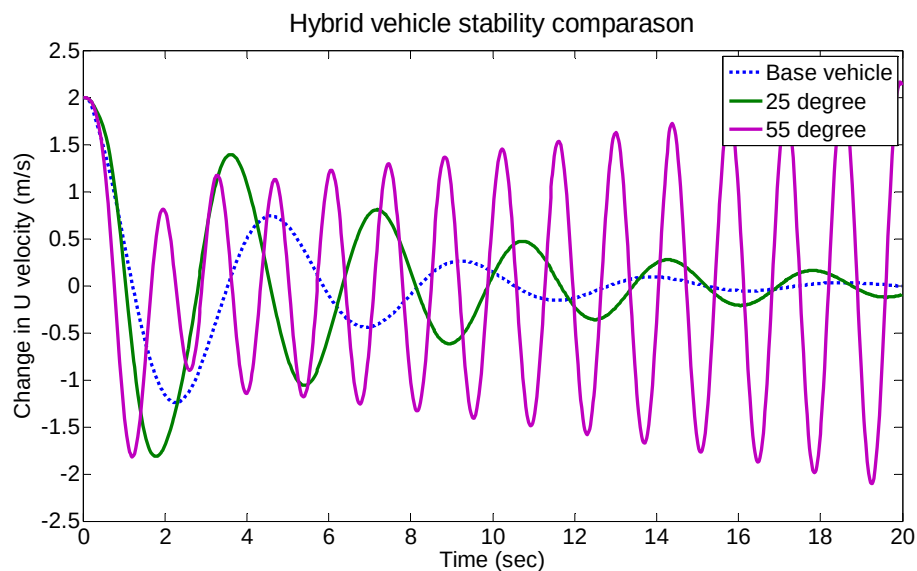


Fig. 20. Longitudinal stability of the hybrid vehicle, change in U velocity

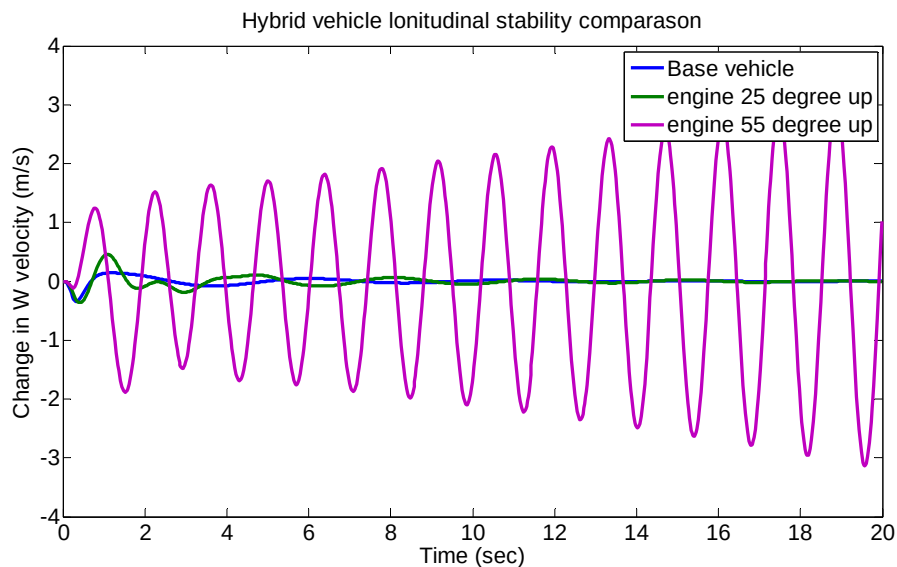


Fig. 21. Longitudinal stability of the hybrid vehicle, change in W velocity

Lateral stability

Laterally, the thrust angle makes MAV to decrease its damping ratio for spiral and Dutch roll mode; however, MAV is still both statically and dynamically stable, therefore less control algorithm modeling should be done in here.

Image Processing – Target suggestion

Application of Hybrid vehicle can be both indoor and outdoor, even though rotating leg has advantages for crossing different terrain and obstacles, but when moving in the flat ground, vibration can cause the image go blur, then leads to heavy mission load for operators [13]

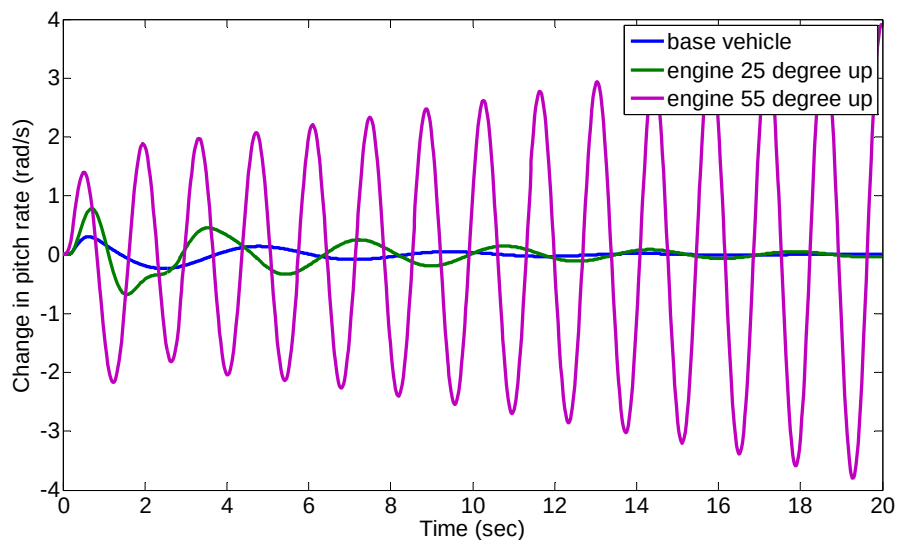


Fig. 22. Longitudinal stability of the hybrid vehicle, change in pitch rate.

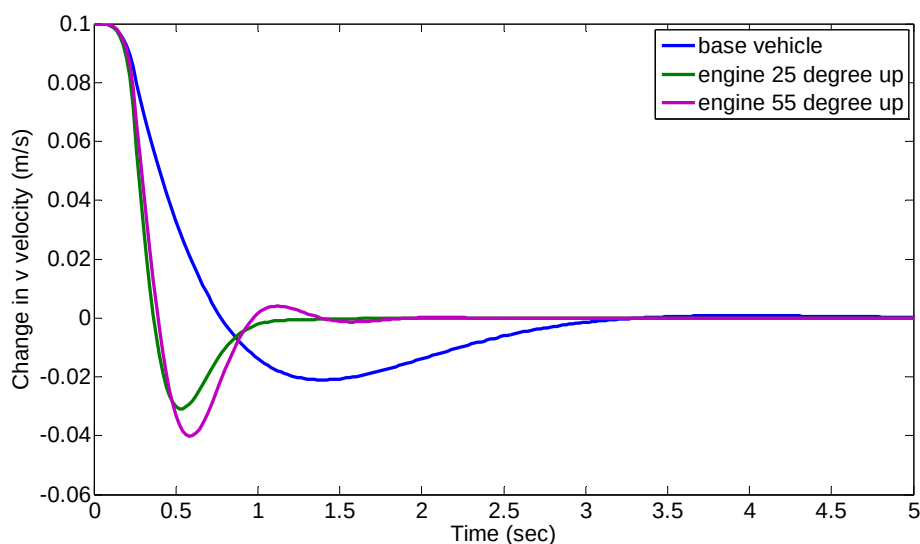


Fig. 23. Lateral stability of the hybrid vehicle, change in V velocity.

In order to lower down the mission load from operator, a simple target suggestion system is designed base on the color pattern.

The system was designed in the way that will suits every different color camera (resolution does not matter in this case).

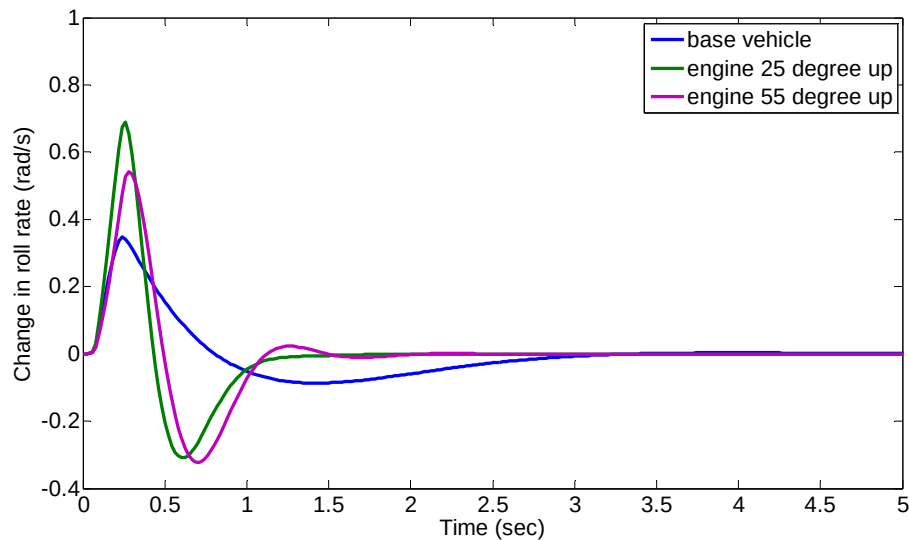


Fig. 24. Lateral stability of the hybrid vehicle, change in roll rate.

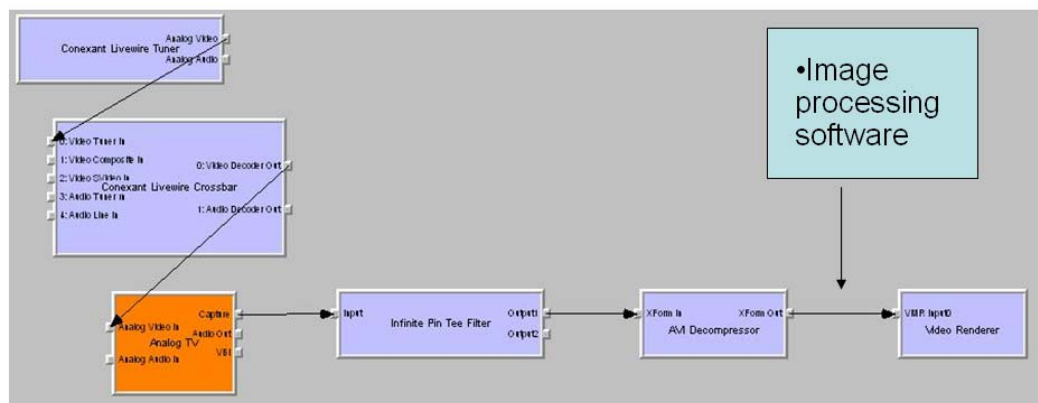


Fig. 25. software block diagram [14]

Output file of the system is bmp picture file, therefore, each pixels are checked, and once the interested pixels has been found (color pattern). In this project, a low resolution warless CMOS camera is used, which means amount of noise signal must be considered, therefore, the software checks the target pixels and pixels around it, if the total number is larger than the threshold value, then it will be indentify as target.

The software architecture allow user to set the color patter and threshold value that is desired for the mission. This method has been tested on larger and slightly higher resolution CCD camera, which gives very positive results (in Fig. 26)

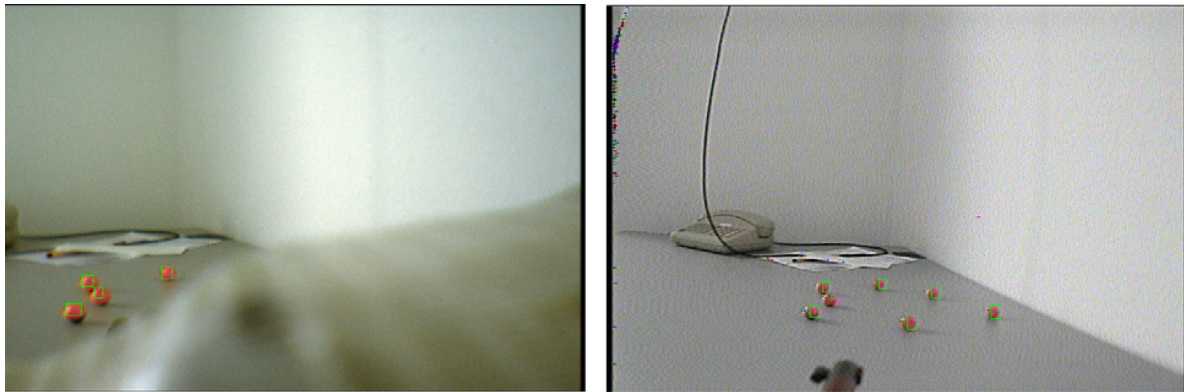


Fig. 26. Left, target system with CMOS camera. Right, same system with CCD camera. Note: software are the same, but hardware are different.

As can be seen on the Fig. 26 the system has capability to identify multiple targets on the same frame. Even though, with only identify color can leads to miss targeting to some non interested object (when to color pattern is similar), but with this system operator could use it as assistance to lower down mission load.

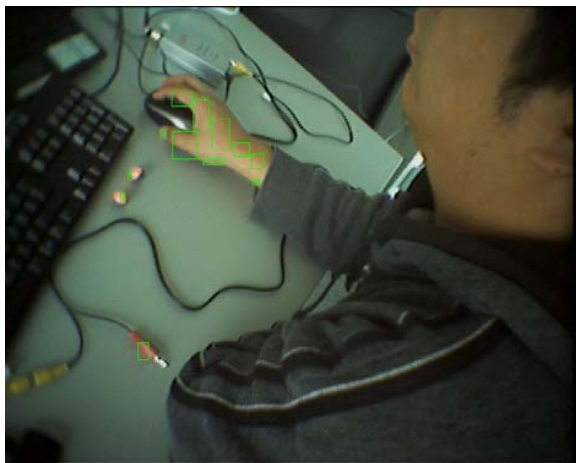


Fig. 27. the target system pick up hand as target as the color (RGB) is very similar to the paintball target.

Image Processing – suspected item detection

Since the design of the software is modular like the MAV platform, therefore the video plug in and targeting system can be re used with minimum modification to create an system that can detect suspected item in urban or out door environment.

The scenario of such system is that hybrid vehicle can fly to the roof of the building at corner of street and land, with the rotating leg, it could then move to desire location such as corner of roof and look down to the street Fig. 28



Fig. 28. Possible scenario, Left, MAV stand on the position to look down. Right, camera view

With out any motor running once the MAV is at location, the power supply for camera and wireless communication can last for few hour, hence it can be form as a mobile CCTV.

Since the mission can last for hours or even for days (depends on the size of power supply and wireless communication range), therefore it is nearly impossible for human operator nonstop monitoring.

Image processing system in this case will first take initial frame by the operator at beginning of the mission, then this frame will be use a comparison. If any object has appear on the camera view which too much different from the original frame, the system will identify the location of the targets, drawn a square around it and then alert the operator. If the target is not a threat, operator can select continuo monitoring the location. If the target is somehow suspected and are moving, then operator could common the MAV to either to change the view angle or even take off again to pursuit the target (this is only possible and also advantage of hybrid vehicle compare with conventional vehicles).

This detection system can also apply on some other vehicle or stationary camera, because modular software architecture allows connecting to different camera, therefore flexibility of missions and equipment selection will be increase, which could lead to faster response time and lower running cost.

Image Processing – Laser range detection

In door navigation is always a challenge topic, since hybrid vehicle is desired to operate in door as well, so the problem must be deal with. One method will be mention in this paper is using image processing technique and laser pointer to measure the distance from vehicle to the wall.

There are many laser range finder available on the market, but the mostly weight around 160g on ward, which is not a lot for conventional ground robot, by for hybrid

vehicle is significant, therefore a different type low weight and cost system should be designed.

Since optical camera is essential equipment for the vehicle, therefore it can be used also as primary sensor for range detection. The basic design of the laser range detector can be seen in Fig. 30

The principle of range detect is similar to system in British bomber Lancaster during WWII[15], the physical distance between vehicle and wall can be determined by the actual distance of two laser spots to the center of the view. The advantage of using two spots is that if the system is in the vertical vibration, the horizontal laser spot will not be affected due to the distance to the center point is not changed. Also with two points system, it forms a redundant system in the real use.

Few experiments were carrying out to construct the mathematical model of the laser system. Some of the typical results of the experiments are shown in Fig. 29.

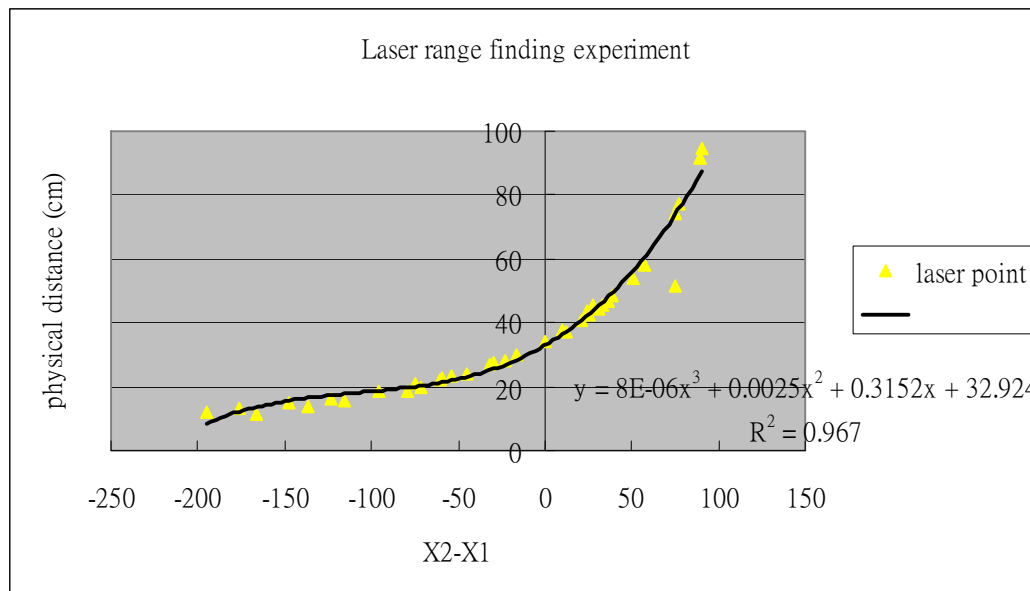


Fig. 29. The laser range finding experimental results

Few experiments had been carried out by the simple RGV platform which vibration is very significant during operation, but the image processing system is able to determine physical distances between wall and vehicle in the indoor situation.

The system performs very well when distance is less than 1 meter, the accuracy is up to ± 2 cm, however, due to physical limitation of the camera resolution and laser output power, the accuracy tend to drop down after 2 meters away from the wall.

Even though, the prototype system is stationary, but hybrid vehicle has designed in the way which leg are independent to each other, which allow 360 degree rotation in the same point, thus allow the laser system to scan the room and environment.

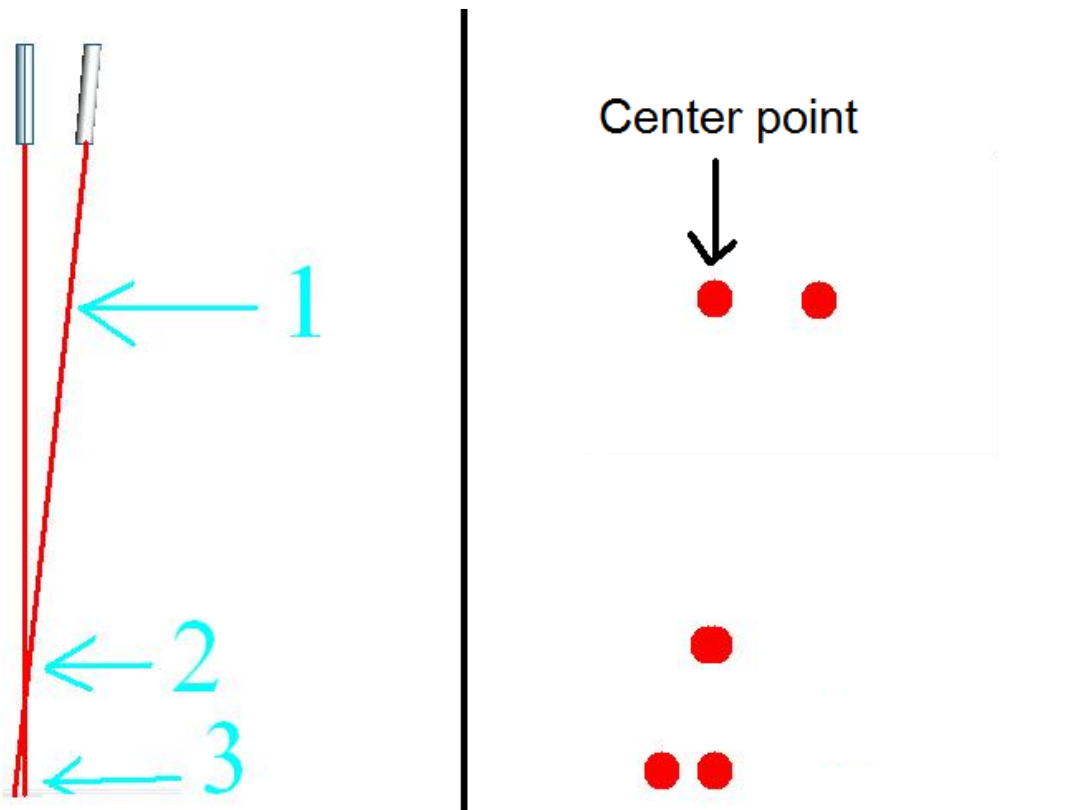


Fig. 30. Left, the principal drawing of the laser system (top view). Right, the laser points show on the plane.

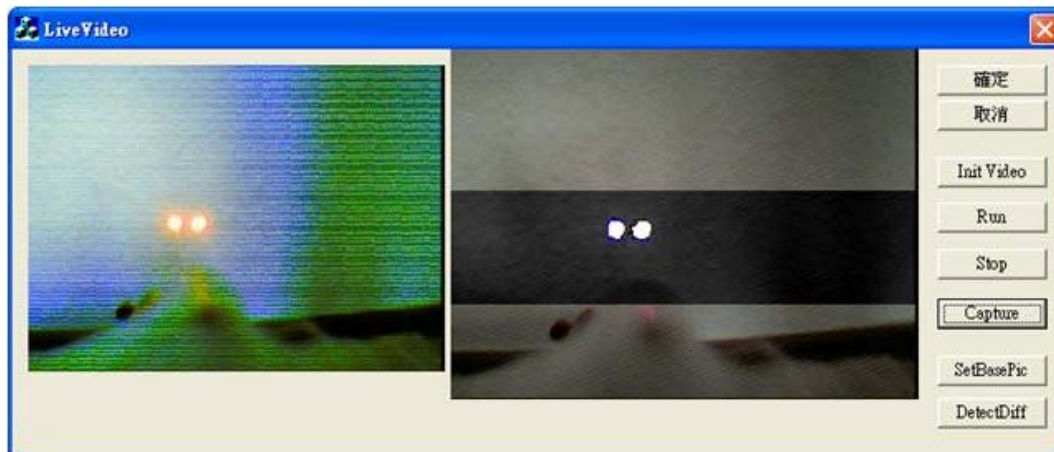


Fig. 31. The GUI of the laser range finder software created by this project.

Conclusion

This paper demonstrated using the modular design methods; the hybrid vehicle design (with off-shelf components) is possible. Bio inspired leg design with conventional optimization allow to create a flexible but yet though “rotating leg” that

is able to protect the RGV or hybrid vehicle. Since using the servos as power drive unit for rotating leg, autopilot software modification was able to keep to minimum. However, without suitable IMU and magneto sensors, indoor operation is only possible by manual control.

Using the vector thrust to change the thrust angle is able to shorten the take-off distance, and the optimized distance can be found by using combination of dynamic equation and CFD results together. However, only problem with vector thrust for assist take off is that shifting CG position too much actually leads to MAV become unstable.

Developing software in the modular design way also allow the rapid development and flexible uses of the hardware, this paper clearly demonstrated the use of different camera and even different system (CCD, CMOS, NTSC and PAL), the results still similar, which allow user to select the camera system that they desired.

Simple target recognition and motion detector can lower down the workload of operator for hybrid vehicle. A novel low cost laser range finder system not just only suitable for hybrid vehicles, but also for other micro robotic uses, as it shows clearly advantage in size, weight and power consumption. The layout of the laser spot allow to filter out mechanical vibration from vehicle itself. Also, two laser spot system forms a redundant system so that if one laser spot fail, reading from other one can be used.

Future work

The hybrid vehicle can still optimize in the control algorithm during the take off, as it is clearly seen in this paper that optimal distance is not the optimal stability. One method of solving the longitudinal stability with the optimal take-off distance is to use CG position adaptive system, which is relate to adaptive structure design and development[4].

Secondly, new type IMU and magneto sensors is required for the indoor navigation, and few example can be seen in Fig. 32

Since the prototype RGV in this paper shows ability to flip over but still operational, therefore, quaritination algorithm must be develop and implemented to the new generation IMU[16],[17],[18].

Third, with more sensors and actuator will leads high power consumption, therefore, higher power supply is needed for the autopilot system, which leads to layout of the current system.

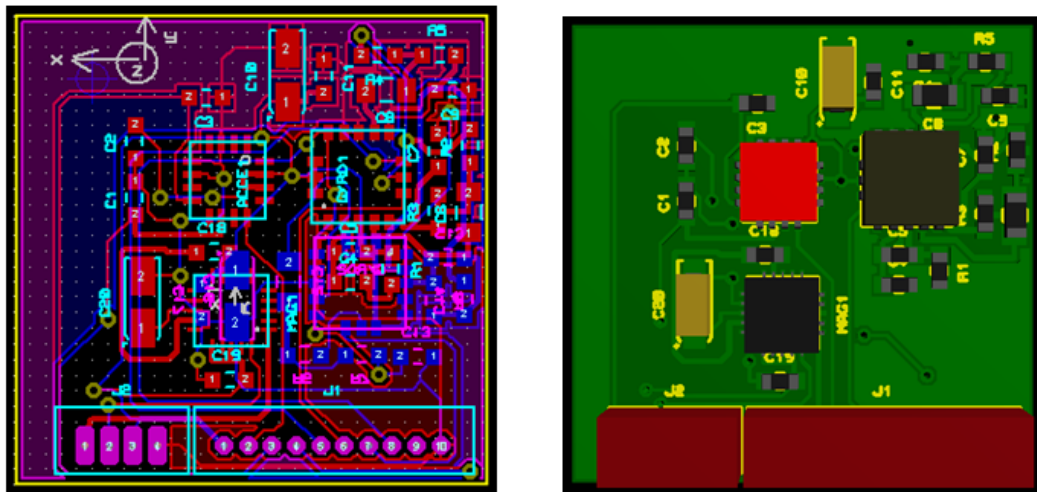


Fig. 32. 6DOF IMU and magneto sensor

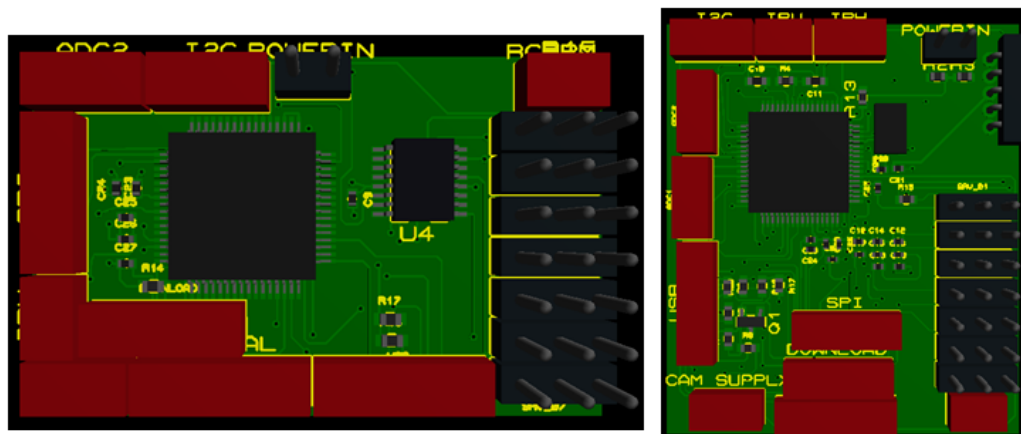


Fig. 33. high power version of the autopilot. Left is 4 x 2.5 cm. Right is 3.5 x 4.1 cm

Third, the image processing system at this paper only look at color pattern, which in particle will have some issue due to noise, therefore, new algorithm combining color and shape should be develop for more accurate target recognition and identification. As for the laser range finder, a more efficient and adaptive algorithm should be develop for automatically changing the parameters for identifying the laser spots on the wall or object at certain distance.

Lastly, and most important factor is to developing dead reckoning navigation algorithm [19],[20],[21] to allow the hybrid vehicle autonomous mission in the indoor situation.

REFERENCE

- [1] Kuo C-M, C Boller and N Qin, 2006: "Adaptive MAV interns of aerodynamic, mission capability and energy efficiency"; Proc. of 2nd European Workshop on Micro Aerial Vehicles, Braunschweig/Germany
- [2] Pablo Pedregal: "Introduction to optimization". Springer. 2003. ISBN:0-387-40398-1
- [3] 李兵, 何正嘉, 陳雪峰. "Ansys workbench 設計, 仿真與優化 (design, simulation and optimization)". 清華大學出版社. 2008. ISBN: 978-7-302-18211-5
- [4] Gordon McComb, Myke Predko. "Robot builder's Bonanza". McGraw-Hill, 2006. ISBN:0-07-146893-5
- [5] Kuo C-M, C Boller and N Qin, 2008: "Modular design of a Micro air vehicle for demonstration of adaptive structure performance"; Proc. of European Workshop on Micro Aerial Vehicles, Braunschweig/Germany
- [6] Kuo C-M and C Boller. "Adaptive winglet design, analysis and optimization of the cant angle for enhance MAV performance" EMAV09 conference. Sep 2009. Delft/Netherland
- [7] Kuo C-M and C Boller. "Demonstration of adaptive structure performance on modular MAV" 18th AIAA/ASME/AHS/SDM adaptive structure conference . Apr 2010. FL, USA.
- [8] J.L Meriam and L.G. Kraige "Engineering Mechanics Dynamics – forth edition". Wiley, 1998. ISBN 0-471-24167-9
- [9] Robert C. Nelson "Flight stability and automatic control". McGRAW-HILL INTERNATIONAL EDITIONS., 1998. ISBN 0-07-115838-3
- [10] Barnes W. McCormick. "Aerodynamics Aeronautics and Flight Mechanics- second edition". Wiley. 1995. ISBN 0-0471-11087-6
- [11] R.P.G Collinson. "Introduction to Avionic System –second edition". Springer. 2006. ISSN 978-1-4040-7278-9
- [12] Brian L. Stevens and Frank L. Lweis, "Aircraft control and simulation –second edition". Wiley. 2003, ISBN 0-471-37145-9
- [13] Douglas Murphya, James Cyconb "Applications for mini VTOL UAV for law enforcement". 1999.
- [14] DirectX wiki. Accessed Mar/2010 Address: <http://en.wikipedia.org/wiki/DirectX>
- [15] The Dam buster. Web accessed. Jan/2010. Address: <http://aviation-history.suite101.com/article.cfm/the-dambusters-wwii-history-summary>
- [16] 楊憲東. "自動飛行控制-原理與實務 (Automatic flight and control- Theory and Practice)". 全華科技圖書, 2002. ISBN: 957-21-3354-3
- [17] Myrian Manai and Adnre Desbiens. "identification of a UAV and design of a Hardware-in-the-loop System for Nonlinear control purposes" AIAA .2004.
- [18] Demoz Gebre-Egziabher and Gabriel H. Eklaime. "MAV attitude Determination by Vector Matching" IEEE Transactions on Aerospace and Electronic System, Vol. 44 No.3 .July 2008.
- [19] D. Gebre-Egziabher, J. D. Powell and P. K. Enge, "DESIGN AND PERFORMANCE ANALYSIS OF A LOW-COST AIDED DEAD RECKONING NAVIGATION SYSTEM"., 2006 .
- [20] K.Venkatraman et al "Sensor – Based Dead Reckoning for land vehicle navigation system". International Journal of Recent Trends in Engineering, Vol 2, No. 4, Nov 2009.
- [21] Lauro Ojeda and Johann Borenstein. W.Ng, "Non-GPS Navigation with the Personal Dead-Reckoning System" SPIE Defense and Security Conference, Unmanned Systems Technology IX. April/2007. Florida/USA