Novel Hybrid Ground/Aerial Autonomous Robot

Mahmoud Elsamanty

Mechatronics & Robotics Eng. Dept.,
School of Innovative Design Eng.,
Egypt-Japan University for Science and Technology, E-JUST
mahmoud.elsamanty@ejust.edu.eg

Mohamed Fanni

Prod. Eng. & Mechanical Design Dept.,
Faculty of Engineering,
Mansoura University
mfanni@mans.edu.eg

Ahmed Ramadan

Computer & Automatic Control Dept.,
Faculty of Engineering,
Tanta University
ahmed.ramadan@ejust.edu.eg

Abstract—**This paper presents a novel robot that combines flying and ground moving capabilities. In doing so, new applications areas for robotics are created in which these two capabilities are needed to perform the tasks. The flying motion will be based on the concept of flying mechanism of the quadrotor. Wheeled mobile platform is combined to the flying mechanism to facilitate ground motion. Transformation mechanism was developed to transform the robot from the ground motion configuration to the flying motion configuration and vice versa. The idea of this mechanism is to close the rotors' arms of the quadrotor and put them in the vertical position when the robot is used for ground motion. This is necessary to enable navigation through narrow spaces. A manipulator with 3-DOF has been added to handle objects during ground motion. After defining the appropriate mechanisms and the basic structure of the robot, geometrical dimensions and material selection of each part are decided. Then, CAD model is developed using SolidWorks, and an iterative process has been carried out to enhance and develop the robot structure and the transformation mechanism. The CAD model was tested using the finite element method in ANSYS14 where static structural study is performed. Finally, motors, sensors and control system hardware were selected for this robot. The analysis indicates the feasibility of the proposed robot.**

Keywords- Flying robot; Mobile robot; Finite element anlysis; Manipulators; Control system.

I. INTRODUCTION

Ground Mobile Robots (GMRs) and Unmanned Aerial Vehicles (UAVs) are of great importance in different fields of the human daily life. One of the robot applications for GMRs is to investigate the areas which are dangerous for the human life [7, 11]. Applications of GMRs are police robots, service robots, indoor and outdoor patrolling, and map exploration. Also they can be used for rescue in urban disaster after earthquake, or to search for victims after building collapses to minimize the risks for the rescuers, and increase the victim's survivals rates. For the Unmanned Aerial Vehicles (UAVs), they have a lot of applications in land security, military operations, civilian applications like monitoring maintenance operations on bridges or in construction sites, and forest fire fighting. They report the location and the size of damage and the main operations are surveillance, and target acquisition [8 - 10]. The most important advantages of this type of vehicles are high speed motion relative to the ground mobile robot, and the easiness of its control [3].

For all previous applications for GMRs, and UAVs; there are some drawbacks in each one. The drawbacks of GMRs are mainly the difficulties to move over terrain with high speed and stability and the complexity of the mechanisms and algorithms to control it. Losing communication with the GMRs is one of the main problems in exploring unreachable area. For climbing stairs, robots need complex mechanisms, with a complex control algorithm. Many other drawbacks can be mentioned like avoiding obstacles, path planning. For UAVs, the drawbacks can be listed as small payload and small flying time. All these drawbacks for GMRs and UAVs were the motivations to develop a new robot that combine the two capabilities to overcome these problems. In doing so, new application areas for robotics are created in which these two capabilities are needed to perform the tasks. The new robot can be used in rescue operation, surveillance, construction operations, firefighting, mining accidents, or in closed places full of poisonous substances (gas, radiation,..). Also, it can be used as a service robot in crowded cities to deliver light stuff such as post mails or quick meals.

The main challenging point in the design of this robot is the compactness. Adding ground motion mechanism, manipulator, and transformation mechanism to UAV necessitates size increase of both flying mechanism and frame. The question is how to achieve a compact design of the hybrid robot that allows ground movement in narrow spaces like traditional mobile robot while has the ability to fly.

The paper presents an illustrative description of a novel robot that can combine both capabilities of UAV, and GMR, and consequently open a new field of applications for robots with multiple capabilities. In order to achieve this goal, a complete new design has been created. Section II describes the whole robot including the design of a new mechanism for closing the rotors' arms to decrease the robot overall size in ground configuration without adding any new actuators. Also it describes a manipulator with 3-DOF which will be added to the robot for object manipulation. Stress and deformation analysis are described in section III together with motors and propellers selection. The control system hardware and its components are presented in section IV. Finally, conclusion remarks are shown in Section V.

978-1-4673-4439-5/12/$31.00 ©2012 IEEE

Authorized licensed use limited to: WASEDA UNIVERSITY LIBRARY. Downloaded on September 16,2020 at 14:05:50 UTC from IEEE Xplore. Restrictions apply.

II. SYSTEM DESCRIPTION

Increasing interest of building GMRs and UAVs with different platforms is a result of increasing robot applications. But there is no robot until now has combined both capabilities of GMR and UAV. The combination of these capabilities in a single robot will create new robotic applications. The main idea of this Hybrid Ground/Aerial Robot "HGAR" is to create a new robot that has two different types of motion; flying , and movement on ground. Flying motion will be based on rotatory blade mechanism while the ground motion will be based on the wheeled platform. Many factors will decide the mode of motion such as ground obstacles, power consumption, and required travelling time. One possible scenario is to decide for flying mode as the main motion mode. After landing on the destination site, the robot switches to ground motion mode and uses its manipulator and wheels to perform the required task. This scenario is suitable for outdoor applications in crowded cities. In case of long flight distance, the robot can land on specific sites where it switches to ground motion mode and recharges its batteries. Then, it switches back to flying mode and continues its flight. This shows how combining flying and ground motion capabilities in one robot increases the flight distance that the robot can achieve autonomously compared to conventional flying robots. Another scenario is to decide for ground motion mode as the main motion mode. After meeting some obstacles like some terrains, walls or stairs, robot has to avoid these obstacles by switching to flying mode. After the robot avoids the obstacles, it returns to land again and continues its ground motion to reach its final goal and completes the task. This scenario is suitable for indoor applications.

The design of HGAR should fulfill some requirements to proof the concept of this new robot. These requirements can be summarized in light weight, stability on ground, navigation through narrow space, and increase of flying time. HGAR transformation process is the sequence of changing robot configuration from one mode to the other. Two different modes of transformations are developed; one is to transform from flying configuration to ground configuration and the other is from ground configuration to flying configuration.

Details of the Flying/Ground transformation are as follow; after the robot finishes its flying mission and lands, HGAR robot needs to start its ground motion using the motorized wheels which are installed in the robot base structure, but the rotor arms occupy large space which leads to difficulty of moving in confined spaces. So, a transformation mechanism is designed to close the rotor arms and bring them from the horizontal position, to vertical position. Then the arms are secured in the vertical position to prevent them from returning back to the horizontal position. The necessary force required to move the arm from the horizontal to the vertical position comes from the propeller thrust force. A securing mechanism will be used to unlock the rotor arm from its fixed horizontal position to be free in rotation about pivot pin. A moment will be induced on the pivot resulted from the thrust force. This moment will lead to rotate the arm about the pivot pin and bring it to the vertical position. Closing the rotor arm leads to decrease the robot lateral size which allows the robot to move through narrow spaces. A manipulator arm is installed on one arm. It will be activated when the rotor arm becomes in the vertical position, where the manipulator becomes in a suitable height similar to the traditional mobile manipulator. For the Ground/Flying transformation, rotor arms are needed to be in the horizontal position. This can be done by inverting the thrust force direction which will push the rotor arm back to the horizontal position. By controlling the thrust forces which come from the rotor propellers, one can decrease the sudden return of the rotor arms and the rotor arm will return to the horizontal position in a smooth way and with minimum impact with the robot frame. Controlling thrust forces will be used in both modes of transformation to avoid impacts with robot frame.

A. Ground Platform Synthesis

The design of the GMR platform is based on a four wheel type [11]. Four-wheel type provides stability in landing as well as in ground motion.The arrangement of these wheels is consisting of two motorized standard wheels, and two free caster wheels or omnidirection type as shown in Fig.1. The axes of the free wheels are perpendicular to the axes of the motorized wheels. Each wheel is assembled to a leg bracket which is connected to the base structure of the robot by four bolts. This leg bracket is designed to maintain the wheel's DC motor inside its frame. To ensure the rigidity of the leg frame during motion, four cylindrical ribs are assembled to the leg frame. One of these ribs will be used to support motor. Large distance between each two opposite wheels gives the robot more stability during ground motion and gives the ability to move over small rough surface. The two motorized standard wheels will simplify the control of the ground motion. Although more motorized wheels increase the maneuverability, they increase the weight of the platform which is not recommended in this application.

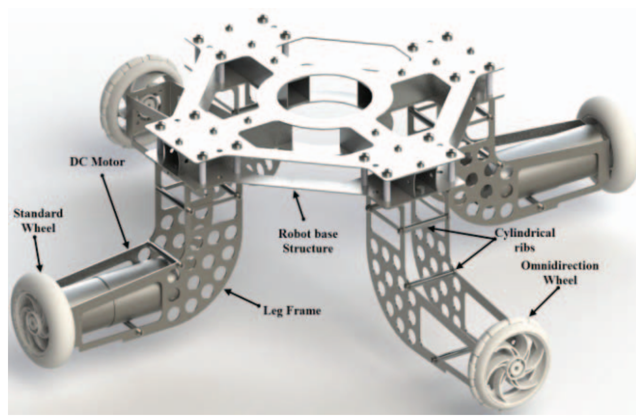

FIGURE 1. MOBILE PLATFORM CONFIGURATION

B. Flying Platform Synthesis

The type of flying platform was selected carefully from several categories of UAVs. UAVs have been classified into two types; fixed wing and vertical takeoff and landing (VTOL) [2, 8, 9]. The need of a runway for takeoff and landing, and the impossibility of hovering are the limitations for fixed wing type of UAV. Therefore, this type was excluded. UAV VTOL type is much suitable for this

Authorized licensed use limited to: WASEDA UNIVERSITY LIBRARY. Downloaded on September 16,2020 at 14:05:50 UTC from IEEE Xplore. Restrictions apply.

application because it has a lot of advantages such as its ability for vertical takeoff and landing, omnidirection flying, stable hovering at low altitudes. UAV VTOL can be classified into different types such as single rotor, quadrotor (QRT), co-axial helicopter, and blimp. A comparison was held between all the types of VTOL-UAV based on different factors such as control, maximum payload, maneuverability, hovering efficiency, and other factors [5, 6, 8]. It is concluded that quadrotor type is the best choice for the flying platform of the proposed HGAR robot.

Then quadrotor platform was designed to support the weight of HGAR structure, batteries, electronics boards and all the auxiliary components. Fig.2 presents the proposed flying platform, which consists of four rotors installed on four arms. These arms have square hollow cross sections and are made from Aluminum alloy to ensure rigidity and light weight. Each arm is pivoted at its end to give the arm the flexibility to rotate about a horizontal axis relative to the platform as requested by the transformation mechanism.

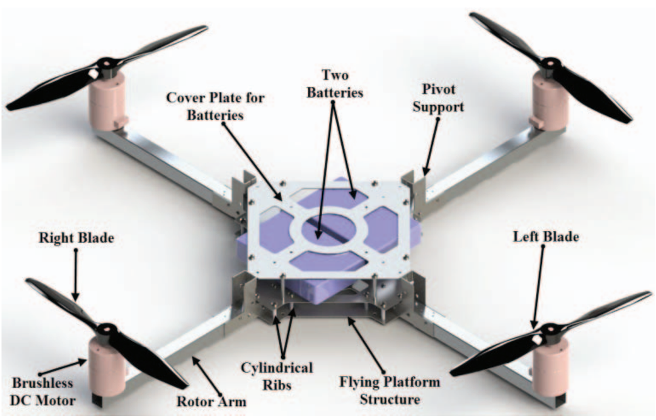

FIGURE 2. FLYING PLATFORM CONFIGURATION

C. *Transformation Mechanism*

The main objective of the transformation mechanism is to reduce the lateral space occupied by the HGAR robot when it is used for ground motion to improve the robot maneuverability in confined spaces. Raising the arms which carry the propellers to the vertical position will realize this objective as showing in Fig.3.

The working principle of the transformation mechanism is unlocking the solenoids of the securing mechanisms, and then the arms will be free to rotate about the pivot pins. The controlled thrust force resulted from the propeller will generate a moment about the pivot pin which forces the arm to rotate about the pivot pin, and becomes in the vertical direction. After the arm reaches to the vertical position, the propeller rotation will be stopped and the solenoids will secure the arm again to the pivot support and prevent it from any movements. The sequence of arms' motion is that each two opposite arms will be rising up at the same time and after reaching to the vertical position, the other two arms will start motion until reaching to the vertical position. Also the propeller blades are provided by a controller to put them in the vertical position when the arms reach the vertical position to prevent the collision between the propellers and to maintain the compactness of the robot. The same working principle is used to transfer the arms from vertical to horizontal position. Only the direction of the thrust forces will be inverted by rotating the propellers in the opposite direction.

This mechanism structure consists of a pivot support which designed especially to maintain the rotor arm in one of two different positions; horizontal or vertical. To secure each arm in its position, two solenoids are selected to be installed inside the hollow space of the arm. This makes the locking mechanism more compact in size. Solenoid's plunger will prevent the arm movement by locking it to the pivot support. These two solenoids will be installed at a certain distance away from each other to improve the arm rigidity with the pivot support, and also to reduce the induced stress as shown in Fig.4. The selection of these solenoids was based on having enough strength to withstand the loads, and having low weight.

D. *Robot Manipulation*

A serial Manipulator with 3-DOF is added to the robot and it is activated during the ground motion mode. A gripper is attached to the manipulator end, all the three joints are revolute joints.

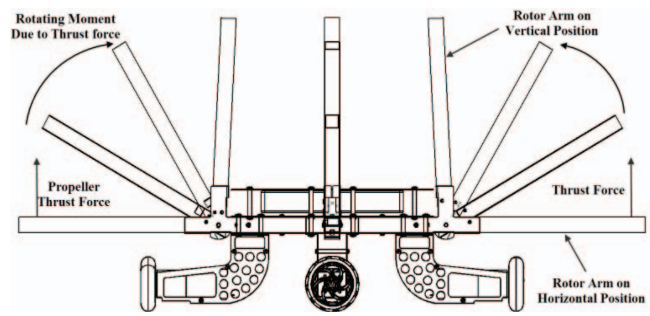

FIGURE 3. CLOSING MOTION OF ROTORS ARMS

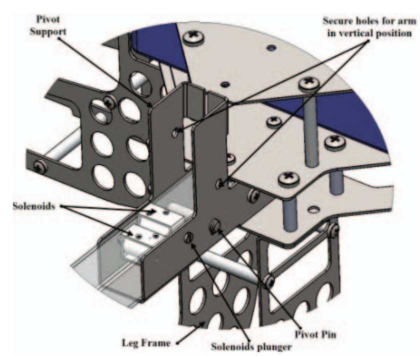

FIGURE 4. DETAILED VIEW FOR THE PIVOT, AND THE LOCKING SOLENOIDS

All the joints are engaged with servomotors. Each joint has working angle of 180^o. All joints axes are perpendicular to each other, when the arm is in its straight configuration. This manipulator provides simple control, light weight and reasonable workspace. The cooperation between the manipulator and the mobile platform will increase the manipulability and the workspace that can be covered by the end effector. This manipulator is fixed on one propeller arm by bolting it from the bottom side of the arm under the center point of the propeller's rotor to maintain symmetry and balance as shown in Fig.5. In flying motion mode this

Authorized licensed use limited to: WASEDA UNIVERSITY LIBRARY. Downloaded on September 16,2020 at 14:05:50 UTC from IEEE Xplore. Restrictions apply.

manipulator will be fixed and maintained in its position as shown in Fig.5. After landing the manipulator will be used when the arm becomes in the vertical position as shown in Fig.6. This puts the manipulator in a suitable height as in the traditional mobile robots. The complete robot in flying configuration is shown in Fig.5 while Fig.6 shows the robot in ground motion configuration.

III. HGAR DESIGN

Fig.7 presents the flow chart for the iterative algorithm of the design process which starts by defining constraints for HGAR such as maximum mass m_{Max} and overall size. Based on the constraints, the propeller diameter and its characteristics are selected and consequently the motor power can be calculated. An initial CAD Model was developed using SolidWorks to estimate the total mass of the robot m_{Max}. Mechanical design was iterated several times to reduce the total mass of the robot, and enhance the strength of the robot in flight and ground motion. The following equation describes robot weight:

$$m_{Max} = m_S + m_{AV} + m_{PM} + m_{bat} + m_{wh} + m_{gm} + m_m + m_c \qquad (1)$$

Where m_s is the mass of the robot structure and it can be roughly estimated based on the CAD model, after selecting material for each part of the structure. The materials of HGAR structure include Aluminum 6063T1, Aluminum 6061, and stainless steel AISI 316. The final estimated mass for the robot structure is 1620 gr. The mass of avionics m_{AV} is about185 gr which consists of the masses of the motors' drivers, flight controller and navy controller.

m_{PM} is the mass of the propeller's motor. The selection of the propeller's motor is determined by an iterative process to calculate the thrust force necessary to lift the robot and force it to fly. The weight of the estimated motors is about 400 gr. The mass of DC motors, m_{gm}, is 340 gr. The four wheels used in this robot are manufactured from plastic ABS to ensure light weight and enough strength to carry the robot weight. The mass of these wheels, m_{wh}, is 110 gr.

Using the transformation mechanism for closing the arms reduces the lateral space occupied by the robot by 62.8%. Two magnetic type solenoids were installed inside each rotor arm. These solenoids are selected to be small enough to be fitted inside the rotor arm. The weight of one solenoid is 8.5 gr. The solenoid plunger has high strength to withstand the applied loads. Two Lithium-polymer batteries are connected in parallel to increase the flight time. Each battery delivers 6600 mAH at 14.8V. The total batteries weight, m_{bat}, is 1430 gr. The mass of the manipulator, m_m, is 120 gr. A camera is installed for localization having a mass, mc, of 375 gr. From equation (1) the total weight of the robot becomes 4525 gr.

A. *Motors and propellers Section*

Selection of propellers is based on the calculations of the aerodynamic forces and moments which provided by the rotors. The propeller used is a fixed pitch type. Fig.8 illustrates the rotor with aerodynamic force and moment acting on it. The governing equations for aerodynamics are expressed as follows:

FIGURE 5. HGAR IN FLYING CONFIGURATION

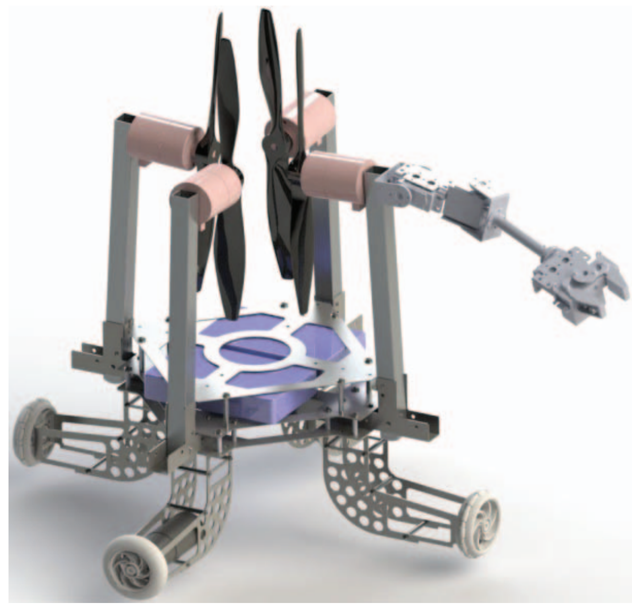

FIGURE 6. HGAR IN GROUND MOTION CONFIGURATION

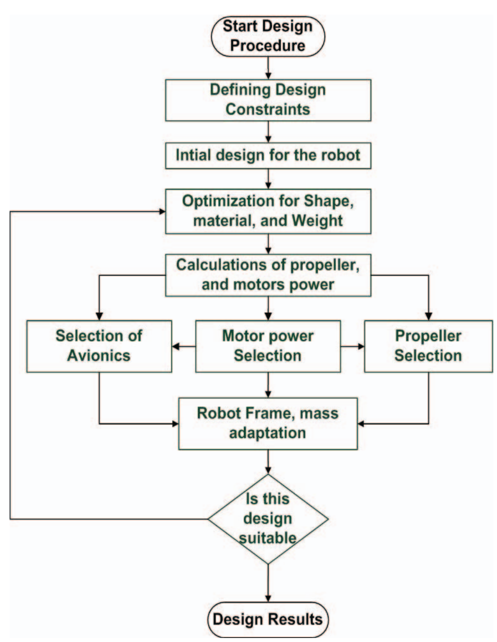

FIGURE 7. FLOW CHART OF THE DESIGN METHODOLOGY

Authorized licensed use limited to: WASEDA UNIVERSITY LIBRARY. Downloaded on September 16,2020 at 14:05:50 UTC from IEEE Xplore. Restrictions apply.

$$T = C_T \rho A (\Omega R)^2 \quad (2)$$

$$Q = C_Q \rho A \Omega^2 R^3 \quad (3)$$

$$P = C_Q \rho A \Omega^3 R^3 \quad (4)$$

Where T is the thrust force acting perpendicular to the rotor plane. The drag moment Q is caused by the drag forces acting on the blade of the propeller. This moment is important to determine the power P of the rotor. The main parameters of the aerodynamic forces and moments are the propeller's area $\boldsymbol{A}$, propeller's radius $\boldsymbol{R}$, thrust coefficients $\boldsymbol{C_T}$, drag coefficients $\boldsymbol{C_Q}$, air density $\boldsymbol{\rho}$, and rotor angular velocity $\boldsymbol{\Omega}$. After finishing an iterative design process, a **CFK** propeller type of 12 inch diameter with pitch angle of 3.8^o is selected to be driven by a brushless **MK3538** type DC motor which has an electrical power of 350 W. The delivered thrust force is 2200 gr at propeller speed of 2850 rpm. The total thrust force which resulted from the four propellers is 8800 gr. The total thrust force is approximately twice the total weight of the robot. So these propellers and motors can produce enough thrust force to make the robot fly.

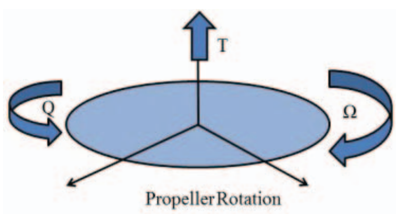

FIGURE 8. AERODYNAMIC FORCES AND MOMENTS ACTING ON THE ROTOR

B. *Stress and deformation Analysis*

The aim of this analysis is to determine the regions in this robot that can exposed to high stresses, or deformation which may lead to failure either from strength or rigidity viewpoint. The results from this analysis will lead to redesign these critical parts which are subjected to high stresses and deformation to prevent them from failure. The results may also lead to redesign the whole robot structure. Finite element method using ANSYS14 have been utilized to perform analysis and optimization for the arms which carry the propellers' motors, Legs of the HGAR, and the complete model of the robot. For the arms, an analysis and optimization were performed to determine the most suitable material, cross section size and weight to withstand the loads. Different materials with different sizes have been assigned to these arms like; Al6061, Al6063T1, Steel 42, Steel 50, and stainless steel. Composite materials are also good alternatives for the robot structure and will be considered in future study. The cross section sizes considered in the analysis vary from 16 mm to 25 mm. The maximum applied thrust force is 2200 gr acting at the end of the arm. The results show that the optimal arm will be made from Al6063T1 with 25X25 mm hollow square cross section and 0.8 mm thickness. According to this analysis, the maximum stress in the arm is 23.48 MPa while 41.8 MPa is the yield strength of Al6063T1. According to this result, the design is considered as a safe design.

Other two analyses were performed on the whole robot model with two different types of constraints. The first one intends to simulate flying mode where fixed supports are made at the thrust forces acting points while all the other forces like robot structure weight, motors weight, batteries, and avionics weight are acting in the downward direction. A meshing process has been performed on the whole model. Meshing on some parts were selected to be tetrahedral elements with 0.5 mm element size, while the rest of the parts were assigned to hexagonal elements with 1 mm element size. The results show that the maximum stress is about 11.94 MPa as shown in Fig.9. Compared to the yield strength of Al6063T1, this value is acceptable. Fig.10 presents the total deformation in the model due to the applied forces. The maximum deformation is 0.06 mm which is too small value indicating the rigidity of the proposed robot. Finally, this model is safe from strength and rigidity viewpoints in the flying mode.

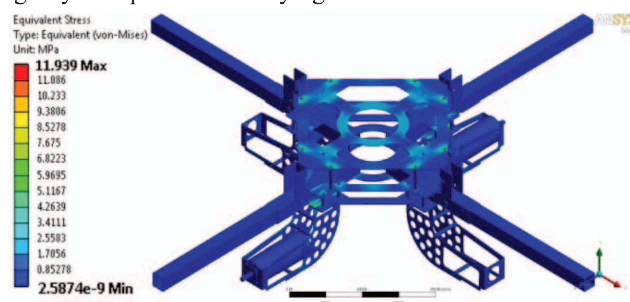

FIGURE 9. EQUIVALENT STRESS FOR THE ROBOT MODEL IN FLYING MODE

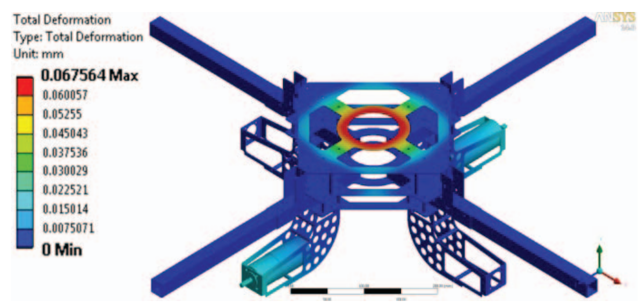

FIGURE 10. TOTAL DEFORMATION FOR THE ROBOT MODEL IN FLYING MODE

The second analysis intends to simulate ground motion mode where the fixed supports are located at the contact points between the wheels and the ground. The meshing and the forces are the same as in the previous analysis. According to this analysis, the maximum stress is about 50.65 MPa, due to the stress concentration zone. These zones are redesigned by adding some fillets. The observed maximum stress becomes 16.885 MPa, and the maximum total deformation becomes 0.318 mm. So, the design is also safe in ground motion mode.

IV. CONTROL MODULES DESCRIPTION

A brief review of the control system and its characteristics for this robot will be presented in this section. The control system of this robot consists of two main subsystems, one for flight control and the other for ground motion control. The control of the transformation mechanism is considered belonging to the ground motion control. The electronics for flight control (Avionics) include motor controller, flight controller, navy controller, radio control receiver, radio control transmitter and flight sensors. Fig.11 presents a detailed diagram for the ground station, flight control and ground motion control.

Authorized licensed use limited to: WASEDA UNIVERSITY LIBRARY. Downloaded on September 16,2020 at 14:05:50 UTC from IEEE Xplore. Restrictions apply.

Multiwii flight board is used for controlling the HGAR during the flying mode. It consists of three axis high quality MEMS gyroscope, three axis accelerometers, three axis compasses and embedded pressure sensor for altitude measurements. The flight board is connected to Navy controller. The Navy board consists of an Arduino mega 2560 microcontroller board. It has 54 pins, which is suitable for connecting the entire ***ESC***-type controller of the brushless DC-motor and all other sensors such as accelerometer, GPS, and Gyroscope to the board. The ground base station consists of PC, connected to RC transmitter through the PC serial PCTX port.

RC receiver is installed on the robot, with 8 channel, and 2.4 GHz. It has a weight of 12 g and its working voltage is 3.6V. The ground motion control system consists of two DC motor controllers, odometer and IR sensor. This control system basically depends on odometer readings to determine the posture of the robot. IR sensor is used to detect any object located in the robot path. The selected IR sensor range is from 0.2 to 1.5 m and its resolution starts from 0.01 to 0.05 m. The selected sensor has a low weight of 7 g, and low power consumption of 5 V, 30 mA.

GPS module is used to improve self-localization of HGAR during flying and ground motion mode and achieving high performance of flight. GPS is helping the system to hold in its position, flight path control, defines the speeds and directions of the HGAR. This GPS module is connected to the navy controller to adjust position and orientation. The selected GPS module is from Skylab SKM53 and it has embedded antenna. Its small weight is 8 gr. Camera is added to the HGAR for target localization, and tracking ground targets to reach the final destination. Small size PTZ camera is selected. It is mounted on two degrees of freedom mechanism. PTZ camera is NTSC type. Its total number of pixels is 410,000 and its focus length varied from 4 to 64 mm.

V. Conclusion And Future Work

The conceptual design and the mechanical design of a novel Hybrid Ground/Aerial Robot, HGAR, are presented in this paper. The key feature of this design is the simple and efficient transformation mechanism that switches the robot between flying and ground motion configurations without the need of additional actuators to close/open the rotors' arms. All the selected mechanisms, actuators, materials and geometrical dimensions were identified to withstand the external forces. The robot CAD Model was tested to verify the strength and rigidity of the proposed robot structure. The analysis shows that the design is safe in both flying mode and ground motion mode. A group of avionics, propellers, motors and measuring sensors were selected for the HGAR. The analysis shows that HGAR design is feasible and the overall dimensions achieve the required compactness of the robot.

As a future work, HGAR will be tested in simulated and real environments to improve its efficiency. HGAR stability will be studied in flying and ground modes. Finally controller will be designed to improve HGAR motion during flying and ground modes.

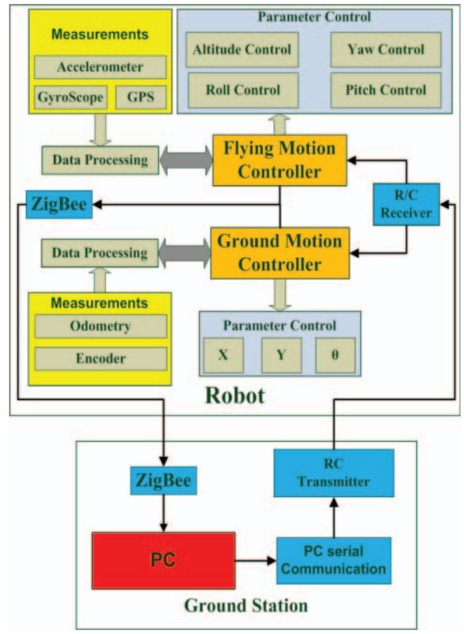

Figure 11. Control system overview

Acknowledgement

The first author is supported by a scholarship from the Mission Department, Ministry of Higher Education of the Government of Egypt which is gratefully acknowledged.

References

[1] C. Bermes, S. Bouabdallah, D. Schafroth, R. Siegwart, " Design of the autonomous micro helicopter muFly", Int. Journal of Mechatronics, Vol. 21, pp. 765-775, 2011.

[2] P. Pounds, and R. Mahony, "Design Principles of Large Quadrotors for Pratical Applications", IEEE international Conference on Robotics and Automation, Kobe, Japan, pp. 3265-3270, May 2007.

[3] B. Erginer, and E. Altug, "Modelling and PD Control of a Quadrotor VTOL Vehicle" IEEE Intelligent Vehicles Symposium, Istanbul, Turkey, pp. 894-899, June, 2007.

[4] Y. Naidoo, R. Stopforth, G. Bright, " Rotor Aerodynamic Analysis of a Quadrotor for thrust Critical Applications", Robotics and Mechatronics conference (ROBMECH), Pretoria, South Africa, Nov., 2011.

[5] H. Huang, G. M. Hoffmann, S. L. Waslander, C. J. Tomlin, " Aerodynamics and control of Autonomous Quadrotor Helicopters Aggressive Maneuvering", IEEE international Conference on Robotics and Automation, Kope, Japan, pp. 3277-3282, May 2009.

[6] S. Bouabdallah, and R. Siegwart, "Full Control of a Quadrotor", IEEE/RSJ Conference on intelligent Robots and Systems, San Diego, CA, USA, pp. 153-158, Oct 2007.

[7] S. A. Moosavian, H. Semsarilar, A. Kalantari, " Design and Manufacturing of a mobile rescue robot" IEEE/RSJ international conference on intelligent Robots and Systems, Beijing, China, pp. 3982-3987, Oct. 2006.

[8] Kimon P. Valavanis, "Advances in Unmanned Aerial Vehicles", Springer, 2007.

[9] P. Castillo, R. Lozano, and A. Dzul, " Modeling and Control of Mini-Flying Machines", Springer, 2005.

[10] K. Nonami, F. Kendoul, S. Suzuki, W. Wang, D. Nakkazawa, " Autonomous Flying robots ", Springer, 2010.

[11] R. Siegwart, and I.R. Nourbakhsh, "Introduction to Autonomous Mobile Robots", MIT press, 2004.

Authorized licensed use limited to: WASEDA UNIVERSITY LIBRARY. Downloaded on September 16,2020 at 14:05:50 UTC from IEEE Xplore. Restrictions apply.