PAZLAT – AN UNMANNED AERIAL REFUELING SYSTEM

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ABSTRACT

PAZLAT is a refueling UAV designed to refuel another UAV. The refueling UAV is based on Israel Aerospace Industries (IAI) "Heron" UAV platform. It was modified to enable fuel storage. Aerodynamic analysis was done to ensure the ability to perform tight flight formation. The refueling instrument is addressed in the paper. The refueling instrument is a rigid telescopic boom. It is automatically guided to its desirable aim point by aerodynamic surfaces. Preliminary capabilities were demonstrated by a model which was built by the project team. The demonstration illustrates how it is possible to perform autonomous aerial refueling between two UAVs. The system guided the boom to the receptacle in a short time, from different starting conditions.

1. INTRODUCTION

Unmanned aviation is constantly developing. Unmanned aircraft perform missions, which were once the preserve of manned aircraft. Their reliability is increasing each year. Once UAV's had to return from their missions because of failure, but today they return from the mission because they run out of fuel.

The existing operational aerial refueling systems are "man in the loop" systems. The refueling aircraft is flown by a pilot as well as the refueled aircraft. The refueling system is operated by a specific crew member. The connection between the two aircraft is based on the skills of the refueling pilot and the system's operator. Unmanned refueling systems allow the air tanker to enter hostile areas with no fear of loss of life. As we see it an unmanned aerial refueling system is a necessity [1, 2, 3].

The preliminary design of the PAZLAT and the demonstration of automatic refueling were carried out as a final project by a group of students, following the basic steps of a new project design. The project combined various aspects such as: configuration, aerodynamics, structure, propulsion and control.

2. PROJECT REQUIREMENTS

The purpose of the project was to develop a low cost aerial refueling UAV, capable of refueling autonomously another UAV.
The project requirements are as follows:

- Low cost aerial refueling system.
- Refueling range: 500[km].
- Refueling speed: 120[kts].
- Refueling altitude: 20000[ft].
- Capability of doubling IAI Heron UAV endurance.
- Minimum changes to the receiver UAV.

3. REFUELING UAV CONFIGURATION

Due to lack of time, the PAZLAT refueling UAV was not designed in detail. Its configuration was derived from the mission definition.

Aerodynamic Configuration

Single engine configuration will allow us to save one of the main costs of the UAV. Rear engine will keep the observation camera, which is needed for the autonomic refueling system, clear of oil and mechanical dirt from the engine. That is why an "H" tail configuration was selected. The engine is mounted on the tail of the main body. Two pylons hold the horizontal stabilizer and the tail. This configuration gives us redundancy for the rear section and keeps the propeller in a close section. A suggestion to keep the extra fuel in the two pylons (instead of the two tubes) was found not suitable in an aerodynamic analyze.

Profile Selection

The wing profile was derived from the mission profile. The profile has to withstand the following requirements:

- Stall speed: 30[kts].
- Minimum drag at 120[kts] (low angle of attack).
- Enable fuel storage inside.

These requirements led us to high thickness ratio profile. Consulting with aerodynamic experts led us to EPPLER E435 profile [4]. The profile contour is shown in Fig. 1. This profile has a $t/c = 0.1624$. It generates high lift at low angle of attack at 120[kts]. It is appropriate for low Reynolds numbers.

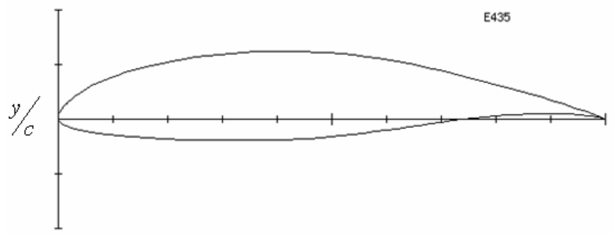

FIG. 1 - EPPLER E435 contour

The selected rear stabilizer's profile is NACA 0012. It is standard profile which is usually in use in tails and stabilizers. It is also appropriate for low Reynolds numbers. NACA 0012 contour is shown in Fig. 2.

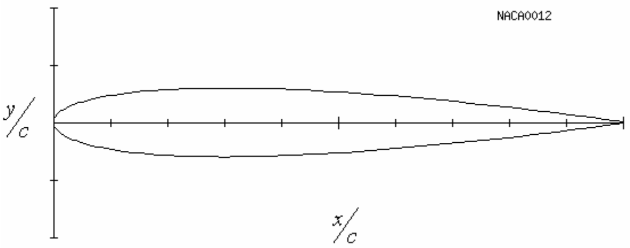

FIG. 2 - NACA 0012 contour

Structural Design

IAI's Heron UAV platform was selected because of its heritage. Its initial takeoff weight is around 1100[kg], and later was extended to 1400[kg] [5]. It is big enough to carry the fuel required double another "Heron" endurance. Its flight envelop is suitable for the mission requirements. Figure 3 describes the "PAZLAT" schematic dimensions. Table 1 describes the "PAZLAT" aerodynamic properties.

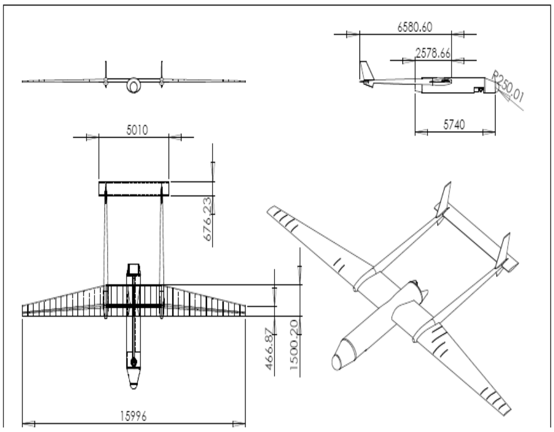

FIG. 3 - Schematic drawing of the PAZLAT. Dimensions are in m"m

Subject	Value
Wing span	16[m]
Wing area	18[m^2]
Wing profile	Eppler 387
Horizontal stabilizer span	5[m]
Horizontal stabilizer area	3.38[m^2]
Horizontal stabilizer	Naca 0012
Tail height	1.25[m]
Tail area	1.4[m^2]
Tail profile	Naca 0012

Table 1 - PAZLAT aerodynamic properties

The two pylon configuration was analyzed structurally [6, 7]. The wing root moment was the main criteria. Although the root moment was smaller in the two pylon configuration, the single body configuration was selected because of its simplicity, and in order to enable gravity based refueling.

Engine Selection

Considering the assumed takeoff weight and mission profile [8], a flight envelop map was built as shown in Fig. 4. The map displays the required engine power versus flight speed and altitude. The wide dark line represents the stalling speed. The green lines represent the cruising working conditions, and it can be seen that a 100 HP engine is needed. Using this map, and after considering weight, cost and fuel consumption the Rotax 914 F engine was selected. Table 2 shows the engine properties.

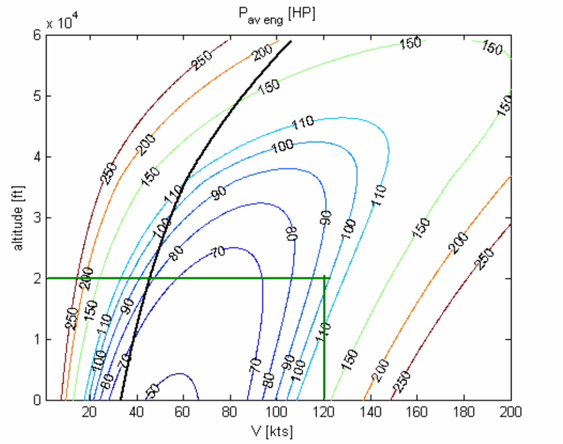

FIG. 4 – Refueling UAV required engine power

Subject	Value
Type	4 strokes, 4 cylinders, liquid/air cooled, turbo charged
Power output	115[HP]
Weight	75.5[Kg]
Specific fuel consumption	0.41[lb/hp/hr]
Price	21,000[$]

Table 2 - Rotax 914F engine properties

Estimated Fuel Fraction

The mission profile was defined:

Takeoff – Climb – Cruise and Refuel – Descent – Land. The calculation based on the assumption that the UAV does not consume fuel during descent and landing. The required fuel weight for the refueling UAV needed to accomplish the mission, versus the refueling range is displayed on Fig. 5.

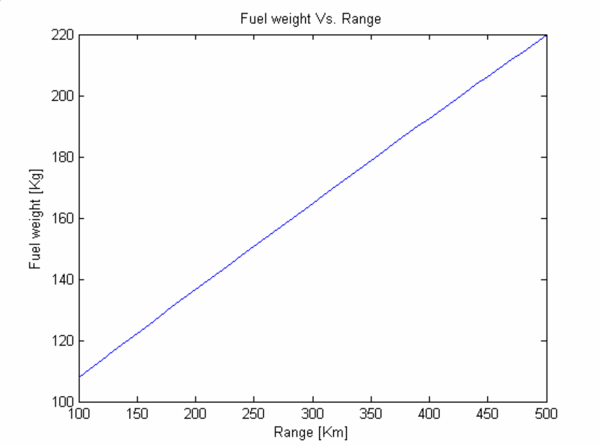

FIG. 5 - Estimated fuel weight for the mission

Fuel Tank and Refueling System Location

As can be seen from above, the refueling UAV has to take about 600[kg] of aerial gasoline, with specific weight of 760[kg/m^3] [9], that means: 800[liters] of fuel. The UAV self consume fuel tank is located in the wing section. The refuel fuel is located in one big fuel tank. The avionics weight balances the fuel tank weight. Because of the rear engine the refueling system has to be located in the front section. Two configurations were considered:

- Front fuel tank, which allows us to locate the fuel tank close to the refueling section. This configuration was found aerodynamically unstable [10].
- Rear fuel tank located close to the UAV center of gravity. This configuration gave us satisfactory aerodynamic stability [11], and is displayed in Fig. 6.

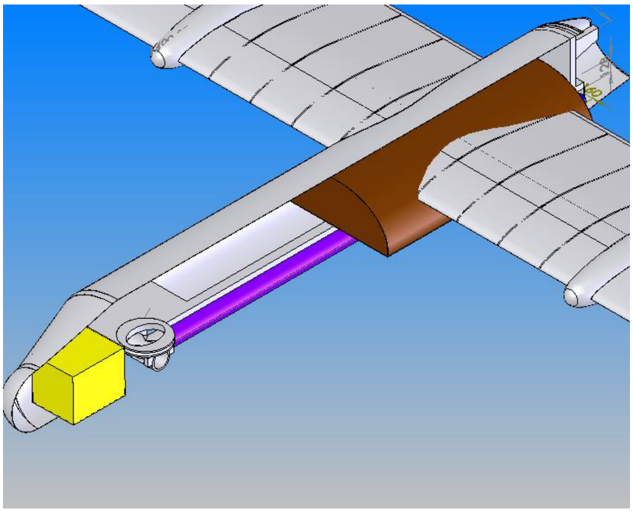

FIG. 6 - Fuel tank configuration

4. REFUELING TECHNIQUE SELECTION

Two common aerial refueling techniques are available [12, 13, 14]:

1. Drogue and Probe. The refueling instrument is composed of a flexible hose with a basket at the end as shown in Fig. 7. The basket stabilized aerodynamically. No exact control ability.
   The main advantage of this method is its simplicity. That is why it is much cheaper.

FIG. 7 - Drogue and Probe refueling technique

2. Boom and Receptacle. The refueling instrument is a rigid telescopic boom. It is stabilized and controlled with aerodynamic surfaces as shown in Fig. 8. The main advantage of this method is its controllability. It can be directed to a specific point in space.

FIG. 8 - Boom and Receptacle refueling technique

The exact controllability of the Boom and Receptacle system led it to be the chosen system, although it is a more complicated and heavier system. In order to reduce the system weight, gravity aided refueling was considered.

Refueling Flight Formation

In order to define the appropriate flight formation that the two aircraft should fly in, a Horseshoe model was implemented. The main goal was to define the relative position of the two UAVs, so the reciprocal disturbance would not exceed the UAV's capabilities. Figures 9 and 10 display partial results. They show the rolling moment coefficient caused by the disturbance of the front and the rear aircraft. Similar results were achieved for the yawing moment coefficients.

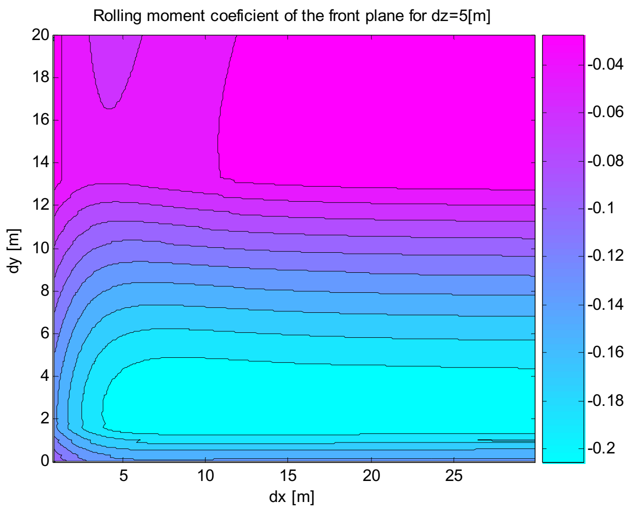

FIG. 9 - Rolling moment coeffiient for the front plane, dz=5[m]

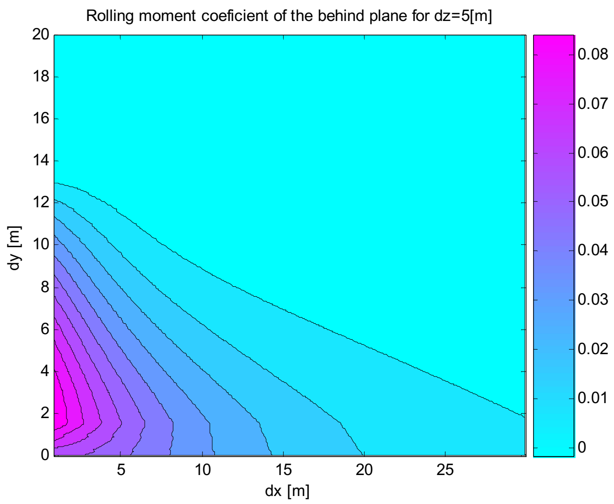

FIG. 10 - Rolling moment coeffiient for the rear plane, dz=5[m]

We decided that the boom would be 12[m] long at the most extended position, enabling the refueled UAV to stay out of the refueling UAV disturbances.

5. SYSTEM LOCATION

The UAV body length is about 5[m], and has a rear engine, so the boom can not protrude from the back section and 3 telescopic sections are required. The rear engine, forces the boom attachment to the UAV body under the nose. Special room was made at the UAV bottom to reduce drag when cruising to and from mission.

6. GRAVITY AIDED REFUELING

In order to reduce system's weight, a gravity aided refueling was considered. Refueling time limitation was defined to be shorter than 3 minutes but not to short, in order to keep the refuel hose small diameter. Viscosity was neglected. The fuel tanks are open to the same surrounding pressure, and the only parameter that affected our calculation was the height deference between the UAVs. Under these assumptions it was found that a 30[mm] hose would transfer 400[kg] in 80 seconds. The calculations were compared to results from "Pipe Flow" computer program, and found similar. The designed boom has a 150[mm] smallest section diameter. At the complete system it should be insured that the smallest diameter won't be smaller than 30[mm]. A simple experiment can be done to ratify these results. Figure 11 shows the required pipe diameter versus the desirable fuel flow rate.

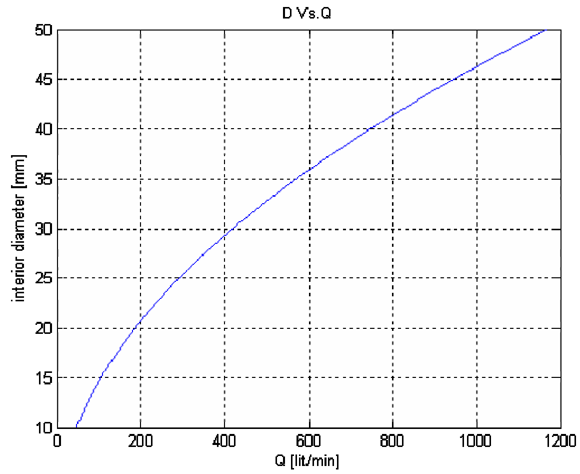

FIG. 11 - Required pipe diameter vs. desirable fuel flow rate

7. REFUELING AERODYNAMICS

In order to guide the boom toward the receptacle, two direction techniques were considered:

- Direction using electrical motors located in the boom's base. Initial calculation showed that the engines should be very powerful, and therefore would be heavy.
- Directions using the aerodynamic forces to move the boom.

The aerodynamic actuation was selected. Two V shape monoblock fins, perpendicular one to the other, 45 degrees above the horizon, are attached to the first section tip as shown in Fig. 12. With this fin configuration boom can be folded into the UAV's body during cruising. A computer controls the fin by mechanic servo motors as discussed later.

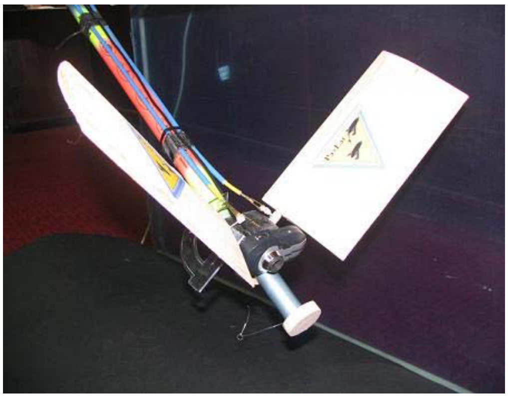

FIG. 12 - The two fins that control the boom

8. BOOM'S STRUCTURAL DESIGN

System Description

As mentioned above, 3 sections telescopic boom was selected. It is free in pitch and yaw movements. It can not roll. Figure 13 displays the entire refueling instrument. The boom is attached to two degrees of freedom base. Special tracks inside the first and second sections prevent the boom from rolling, as shown in Fig. 14.

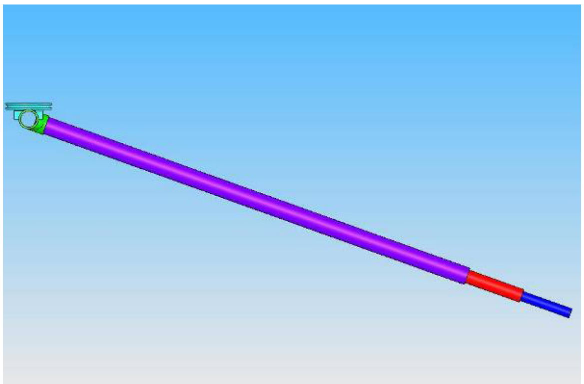

FIG. 13 - The entire refueling instrument

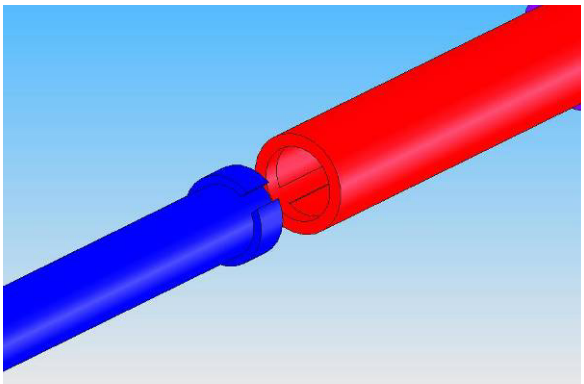

FIG. 14 - Close up of the 2nd and 3rd sections

Strength Analysis

The boom is influenced by 3 forces: drag, weight and fin's lift, which is the only controllable force to bring the boom to equilibrium around the base axe. Assume all boom's sections have the same thickness. Weighting the entire stresses results from the forces, and comparing it to graphite epoxy composite material's strength, led the resulted thickness requirement: $t = 7.5[mm]$.

Optimization on the boom's inner and outer diameters brought the results:

- Outer diameter: 200[mm].
- Inner diameter: 155[mm].

Under these assumptions the boom's weight is about 90[kg].

Bending moment distribution along the boom is shown in Fig. 15.

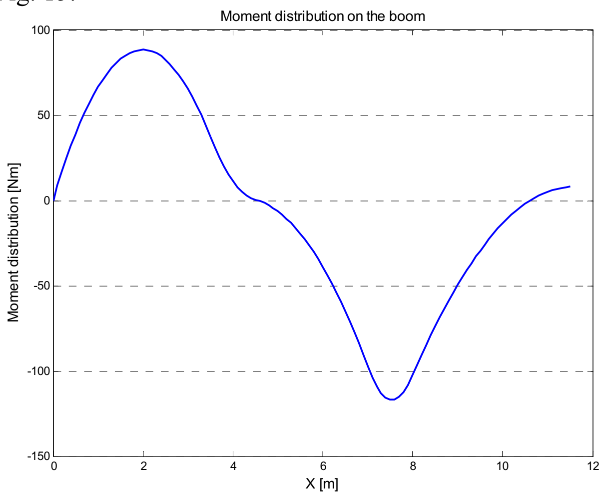

FIG. 15 - Bending moment along the boom

9. SCALED MODEL DESIGN

In order to illustrate the capability of autonomous refueling process, a scaled model, and a small wind tunnel were built. The model illustrates the ability of directing the boom toward the receptacle by using a simple control system, composed of low cost components. The relative movement between the two UAVs was neglected in the model.

Model Structural Design

The model was built from simple materials which were available. The boom was made from a fishing rod. The fins and their base were made of balsa wood. Regular flying model's servos moved the fins [15]. The selected fin's profile is: NACA 0009, which is a standard profile for subsonic stabilizers. Gravity causes the boom to lengthen and a wire, attached to one of the servos, passes through the boom and controls its extension. The model is displayed in Figs. 16, 17 and 18.

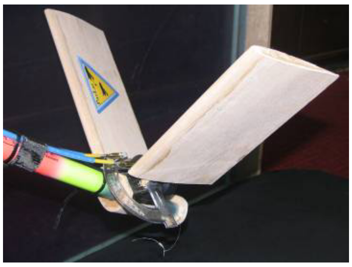

FIG. 16 – Left view of the model

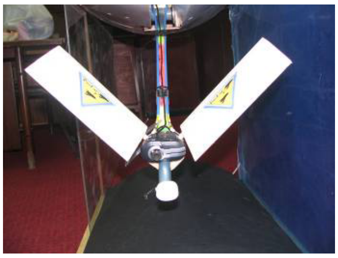

FIG. 17 - Rear view of the model

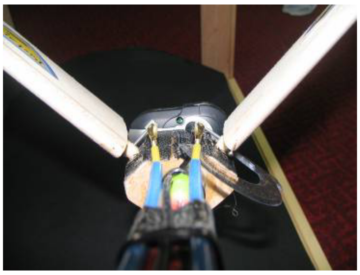

FIG. 18 - Front view of the model

The model was inserted into a wind tunnel made of wood and Perspex. It was operated by an industrial fan. The approximated wind speed inside the tunnel was 10[m/sec]. Because of the slow wind speed, a weight helped balance the boom. The designed wind, with the boom located inside, is shown in Figs. 19, 20, 21 and 22.

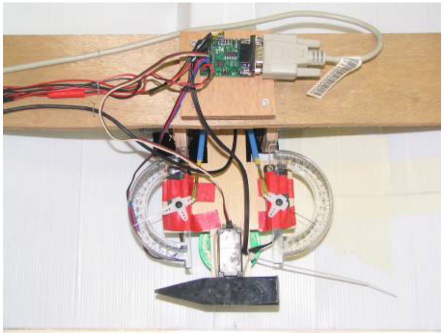

FIG. 19 - Upper view of servo control unit

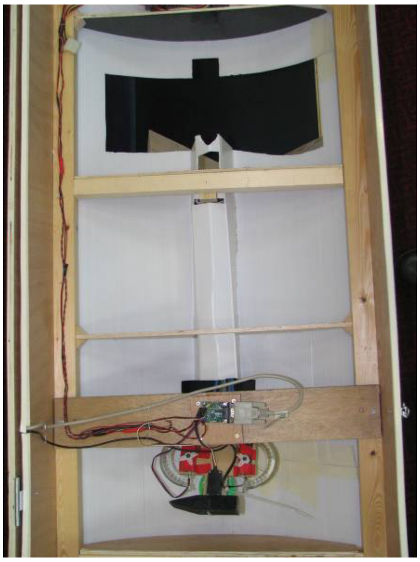

FIG. 20 - Upper wind tunnel equipment

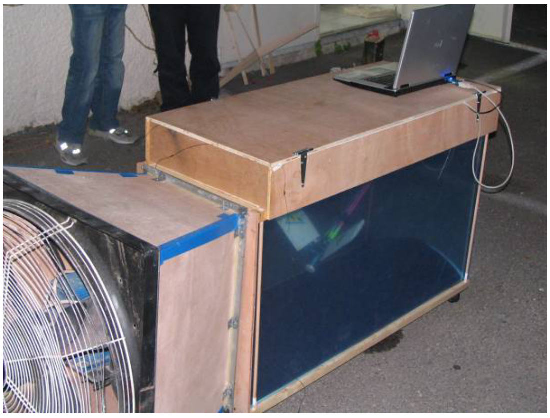

FIG. 21 - Right view of the entire model

FIG. 22 - Left view of the entire model

Control System Design

Optical control system was selected. The receptacle is marked with red LED. Another green LED indicates successful attachment between the boom and receptacle. USB internet camera is attached to the boom, as shown in Fig. 17. Computer uses image processing to produce the relative receptacle position. It calculates the angular error to be reduced, and translates it to servo movement commands. A schematic diagram of the system is shown in Fig. 22.

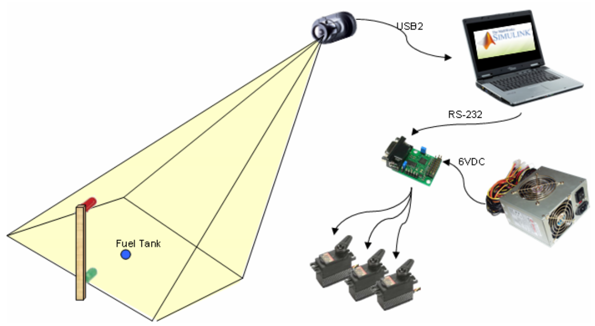

FIG. 23 - Schematic diagram of the control system

A PI with lead compensator controller was selected to implement the control algorithm. The controller transfer function is:

$$C(s) = \frac{0.51964(s+16.67)}{s}\,\frac{(s+11.9)}{(s+34.48)}$$

Its open loop bode diagram is shown in Fig. 24. The system root locus diagram is shown in Fig. 25.

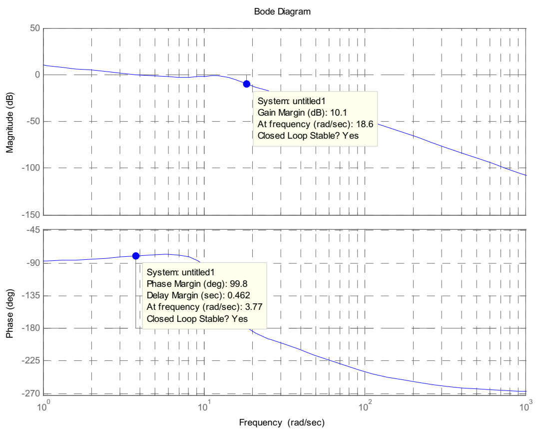

FIG. 24 - Open loop bode diagram

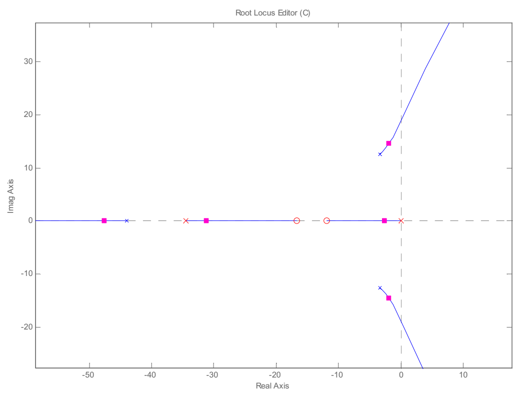

FIG. 25 - System's root locus diagram

The response to step input is given in Fig. 26.

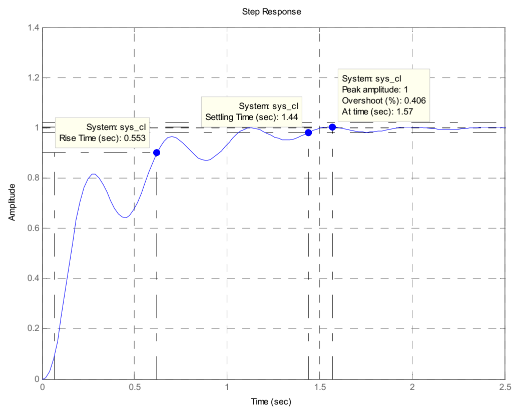

FIG. 26 – System's step response

The computer constantly calculates the angular error. When the errors are small enough the computer commands the boom to lengthen. When the attachment is accomplished and green LED is lightening, the computer stops the boom's extension. General Stateflow of the control algorithm is given in Fig. 27.

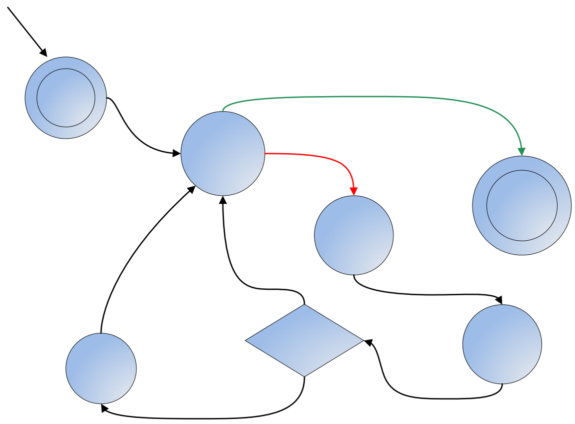

FIG. 27 - General control algorithm stateflow

The tracker system allows the computer find the receptacle. Schematic diagram of the tracker system is given in Fig. 28.

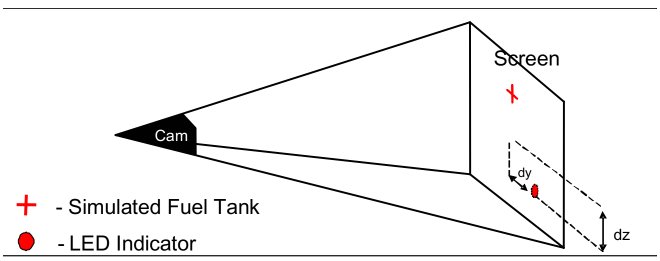

FIG. 28 - Tracker system scheme

The control algorithm, image processing and servo control were implemented by Simulink tool boxes, which is a part of Matlab.

10. PERFORMANCE

Several experiments took place. They differed from each other in initial errors, and under different disturbances. Typical experiment results are given. The initial errors were: 7[deg] in yaw and about 9.85[deg] in pitch. Figure 29 displays the angular errors calculated by the computer during the process. The 3rd subplot represents the lengthening command. It can be shown that the extension command is given only after the angular errors were reduced. Figure 30 displays the commands the computer gave to the fins. Saturating commands were given, and explaining the constant command the computer gave to the fins at the process's beginning can be seen in the graphs.

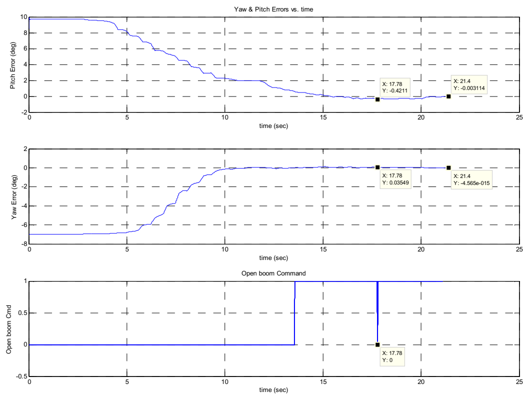

FIG. 29 - Angular errors and extension command

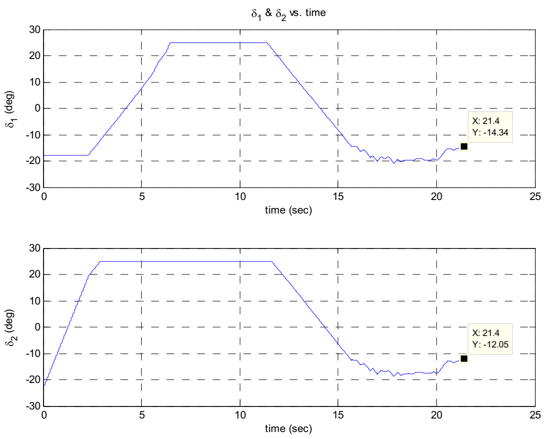

FIG. 30 - Fins commands

At the end of the process the boom is connected to the receptacle as can be seen in Fig. 31.

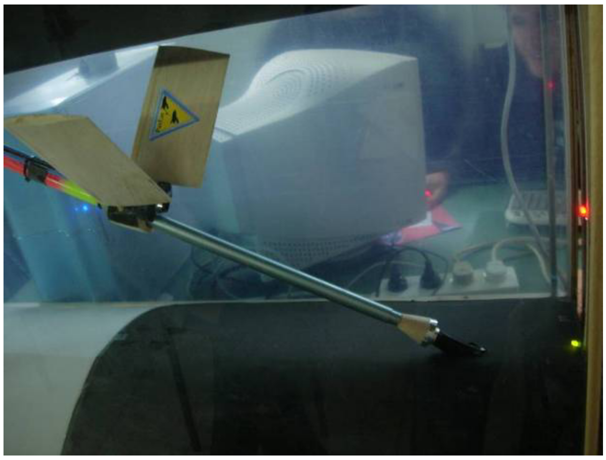

FIG. 31 - The system at the end of the refueling process

11. FUTURE RESEARCH

In order to complete the design program, there are more points of interest to examine:

- The refueling UAV- In order to simplify the problem, and achieve a significant result the "Heron" UAV platform was selected. It is obvious that an aerial refueling system should be based on a market research.
- Refueling UAV maneuver – The selected approach maneuver was designed so that the refueled UAV just fly straight and level. It should be investigated if it can cooperate with the refueling UAV.
- Fuel type - The existing refueling systems are designed for jet fuel. Gasoline is a different fuel that needs different treatment, which should be defined [4].
- Gravity aided refueling needs additional investigation.
- The refueled UAV changes plan should be defined.

12. CONCLUSIONS

PAZLAT is an autonomous aerial refueling system. It was designed to enable aerial refueling from one UAV to another. In order to achieve this unique concept the students had to use methods of preliminary design similar to those in industry. The students used their knowledge and experience during the planning. They defined the requirements, learn and investigated a foreign field for most of them, and gave the best solution they could find. All this was achieved thanks to hard individual and collective work.
The students had to deal with many problems, especially during the model integration.
The result presented in this paper show that autonomous aerial refueling is possible.
The suggested system is a telescopic boom composed of 3 sections. It is guided by aerodynamic surfaces. The autonomous refueling procedure is controlled by a computer, using image processing. A scaled model was

built in order to demonstrate the attachment procedure in a wind tunnel. During the demonstration the computer calculated the angular error between the boom and receptacle, and moved the aerodynamic surfaces to decrease the errors. When the error was small enough, the boom was lengthened until attachment occurred. Usually the attachment was accomplished in less than 1 minute.

There is still a long way to go until it would be operational, but the PAZLAT model proves this claim. The attachment was achieved in spite of low budget and the very simple material used.

13. ACKNOWLEDGEMENTS

The PAZLAT team would like to thank Mr. Robert Zickel and Mr. Itzik Klein for their guidance and assistance in this project.

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