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Modelling, Simulation and Navigation Experiments of Unmanned Aerial Vehicle

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Abstract— UAV is an aircraft without pilot which can fly autonomously. It can fly at a desired altitude, velocity and point exactly by using GPS, attitude system and barometer in a vehicle. It is also able to follow an arbitrary trajectory by designating waypoints. The UAV targeted in the current study is a solar-powered UAV which is a joint research project between Tokai University and King Abdulaziz University of Saudi Arabia. Study of solar UAV started about 40 years ago. As the joint research effort Sunfalcon 1 was developed. This report describes modelling of the aircraft to be used for building a flight simulator. Then the model obtained is tested for an altitude tracking control simulation.

Keywords— UAV, Simulation, ArduPilot, Mission Planner, Datcom+ Pro, Flight test,

I. INTRODUCTION

According to WIKIPEDIA, UAV (Unmanned Aerial Vehicle) is an aircraft without a human pilot aboard. There are two types in UAV, autonomous aircraft and remotely piloted aircraft. Preferred tasks for UAVs are missions that are too "dull, dirty or dangerous for manned aircraft [1].

Tokai University and King Abdulaziz University of Saudi Arabia started a joint research project on development of a solar-powered unmanned aircraft in 2012. Many students of both universities have been involved in the project as a project-based learning platform. The ultimate goal of the project is to achieve a day-and-night flight using batteries charged by solar power.

The first success of solar powered UAV goes back to 1974 when R. J. Boucher designed Sunrise I [2]. Because of the recent, rapid increase of power generation efficiency, there has been an ongoing research on solar airplane which is able to fly continuously over 20km of altitude for 5 years [3].

This study is aimed at developing a flight simulation environment of the solar airplane, based upon which a navigation system will be built. The solar airplane is assumed to be equipped with GPS, IMU, pressure sensor, altitude sensor, etc. Typically these sensors allow UAVs to navigate along a series of subgoals called waypoints which are placed along a desired trajectory.

This report describes modelling of the aircraft "Sunfalcon 1" shown in Fig. 1 which we built as a first prototype before

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building a full-fledged solar airplane. Then the model obtained is tested for an altitude tracking simulation. Also in parallel to the development of the simulation environment, we conduct preliminary real flight experiments where the Sunfalcon 1 is commanded to follow a series of waypoints which are allocated along a circular trajectory. Through the experiments an optimal choice of control parameters is identified.

II. EXPERIMENTAL HARDWARE AND SOFTWARE

A. ArduPilot

The microcomputer mounted on the experimental aircraft is ArduPilot which is commercially available through 3DRobotics Inc.[4]. ArduPilot is based on the Arduino open-source electronics prototyping platform [5], being equipped with IMU (Inertial Measurement Unit), GPS, pitot tube, pressure sensor, etc. It is a full autopilot capable for autonomous stabilization, way-point based navigation and two way telemetry. It also allows time stamped data logging.

There are a variety of source codes available for ArduPilot on the Internet. User can pick up any working code sample and modify it to his/her own needs. In the study, we employed an existing source code for the stable flight of an aircraft.



Fig.1 Outlook of Sunfalcon 1

B. Mission Planner

ArduPilot has many built-in parameters related to an aircraft. Adjustment of those parameters enables users to set limits to the pitch, bank, and yaw angles, or to control the aircraft body movement under the autopilot mode. Mission Planner is a ground control station for ArduPilot, loading the program into

the ArduPilot and setting up, configuring and tuning the aircraft for optimum performance. Other features of the Mission Planner are:

- Allowing point-and-click waypoint entry on Google,
- Downloading and analyzing mission logs,
- Interfacing with a PC flight simulator to create a hardware-in-the-loop simulator,
- Monitoring the vehicle's status with telemetry while in operation, and
- Viewing and analyzing telemetry logs.

A sample display of Mission Planner is shown in Fig.2.

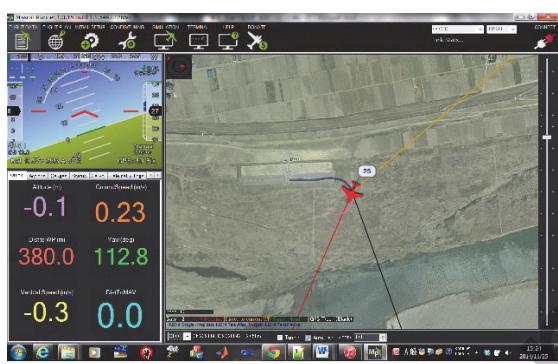


Fig.2 Mission Planner

C. Sunfalcon1

The aircraft used for experiments was designed and developed at the Department of Aeronautics and Astronautics of Tokai University, called "Sunfalcon 1". ArduPilot is installed in Sunfalcon 1 and autonomous navigation missions are planned and monitored by the aforementioned Mission Planner. Take-off and landing are controlled manually for sake of safety. Manual operation mode and automatic operation mode can be switched back and forth by using a toggle switch.

The main specifications of Sunfalcon 1 [6] are listed in Table 1.

TABLE I. SPECIFICATIONS OF SUNFALCON 1

Body	
Body length[m]	2.6
Wing Span[m]	3.7
Body height[m]	0.13
Configuration of Main Wing	
Cruising CL [-]	0.4
Aspect Ratio [-]	9.2
Main Wing Area [m ²]	1.49
Mission	
Cruising Speed [km/hour]	50
Cruising Altitude [m]	100
Payload [kg]	0.6
Endurance Time [hours]	10
Rate of Climb R/C [m/s]	2
Cruising Speed [km/hour]	50
Cruising Altitude [m]	100
Given Data	
Efficiency of Motor and Propeller [-]	0.45
Cruising Power and Energy	
Total Drag [N]	3.72
Required Thrust [N]	3.72
Required Total Energy[Wh]	803
Battery	
Number of 4cel Li-ion battery[-]	1
Total Battery Mass [kg]	0.73
Mass	
Horizontal center of mass[m]	0.827
Vertical center of mass[m]	0.164
Airframe Mass [kg]	2.32
Total Mass [kg]	5.55

D. Datcom+ Pro

Modelling of Sunfalcon 1 is carried out by using Datcom+ Pro made available from Holy Cow Inc. Datcom+ Pro is a user-friendly extension of Digital Datcom which was a computer program originally developed in the 1960's to 1970's by the United States Air Force for designing and analyzing an aircraft. Visualization tools provided by Datcom+ Pro allow the user to see his/her aircraft immediately, and coefficient data generated is plotted on X-Y graphs for ease of interpretation.

Datcom+ Pro requires an input file containing a geometric description of an aircraft, and outputs its corresponding dimensionless stability derivatives according to the specified flight conditions. The input file is mainly comprised of five

elements, main aircraft body, main wing, horizontal tail, vertical tail, and miscellaneous conditions such as a flying environment.

Each element allows inputs of detailed values to define the geometry of the element. For example, the main body allows as many as 20 sections each of which is specified by width, height and length of circumference with the assumption of an axi-symmetrical shape for the body. All the values are referred to a common coordinate frame whose origin is typically placed at the nose of the main body. Flaps, elevators, and ailerons can be defined individually while rudders are not supported [7].

Mathworks' Aerospace Toolbox includes a function for importing output files from Datcom+ Pro into MATLAB® environment. This function lets the user collect aerodynamic coefficients from static and dynamic analyses and transfer them into MATLAB® as a cell array of structures. With a combination of 3D Animation Toolbox, one can develop his/her own flight simulator in MATLAB®.

III. EXPERIMENTAL PROCEDURES

A. Simulation

The aircraft model of Sunfalcon 1 is obtained by Datcom+ Pro. The output produced by Datcom+ Pro is imported into MATLAB®/Simulink environment by running “datcomimport” function which creates a cell array of structures containing the data from the Digital DATCOM output file. The model imported is tested for an altitude tracking control by using a PID controller.

Fig.3 shows the flow diagram of the main blocks used in simulation in which the big box trimmed in green color represents the model of Sunfalcon 1 generated by Datcom+ Pro.

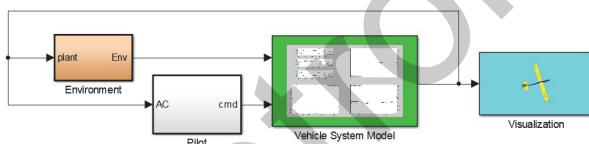


Fig.3 Simulation blocks in MATLAB®/Simulink

B. Flight experiments

The flight experiments were conducted on the special runway dedicated to the use for RC vehicles. The place is called “Ojima Sky Port” which is located in about 120 km north of Tokai University.

In this experiment, among many parameters defined in ArduPilot, we decided to choose the following three parameters which are closely related to a way-point navigation.

1. LIM_ROLL_CD: the maximum commanded bank angle in either direction (unit: centi-degrees). Default is 3000.
2. WP_RADIUS: the maximum distance from a waypoint that when crossed indicates the waypoint may be complete (unit: meters). Default is 40.
3. NAVL1_PERIOD: period in seconds of L1 tracking loop. This parameter is the primary control for aggressiveness of turns in auto mode. Default is 25.

The parameter setting employed in the experiment is listed in Table.2. The altitude and throttle power are fixed at 100m and 50%, respectively. The number of way-points used is six and the circular trajectory connecting the way-points has a radius of 300m.

TABLE II. EXPERIMENTAL CONDITIONS

1st	
LIM_ROLL_CD[cdegree]	1000
WP_RADIUS[m]	50
NAVL1_PERIOD[seconds]	30
2nd	
LIM_ROLL_CD[cdegree]	1500
WP_RADIUS[m]	50
NAVL1_PERIOD[seconds]	30
3rd	
LIM_ROLL_CD[cdegree]	2000
WP_RADIUS[m]	50
NAVL1_PERIOD[seconds]	30
4th	
LIM_ROLL_CD[cdegree]	1000
WP_RADIUS[m]	90
NAVL1_PERIOD[seconds]	30
5th	
LIM_ROLL_CD[cdegree]	1500
WP_RADIUS[m]	90
NAVL1_PERIOD[seconds]	30
6th	
LIM_ROLL_CD[cdegree]	2000
WP_RADIUS[m]	90
NAVL1_PERIOD[seconds]	30

IV. EXPERIMENTAL RESULTS

A. Result of Modeling and Simulation

The model of Sunfalcon 1 produced by Datcom+ Pro is shown in Fig.4. The ailerons and the elevators are colored in blue and in red, respectively. The rudder does not appear in the vertical tail because a rudder is not implemented in Datcom+ Pro as mentioned before.

The model is applied to an altitude tracking control simulation using PID control. The results are shown in Fig. 5 and Fig. 6. The red curve and blue curve in Fig.5 represent the target altitude and the vehicle response, respectively. In Fig. 6, the top figure shows the altitude change while the bottom figure shows the head angle.

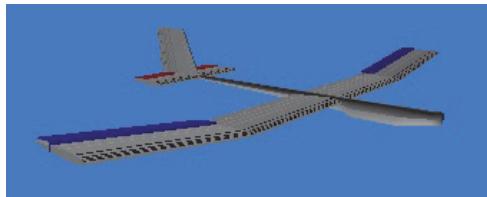


Fig.4 Geometric model of Sunfalcon 1

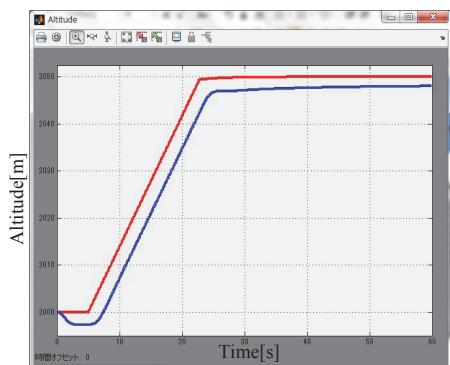


Fig.5 Target value (red) & actual altitude (blue)

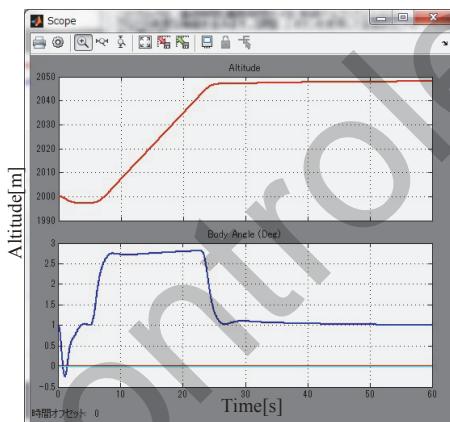


Fig.6 Altitude (top) and head angle (bottom)

B. Flight test

Among six attempts of the flight test, the first round failed in data logging. Therefore the results of the second round through sixth round are depicted in Fig.7 ~ Fig.11 in which the blue curve represents the trajectory in manual pilot mode while the brown curve the trajectory in auto pilot mode. Note that these

figures are plotted in longitude/latitude pair instead of X/Y coordinates.

According to the results, it is seen that the trajectories in auto pilot mode for Fig. 7 ~ 9 show departures from the ideal circle and the vehicle failed to pass through some of the way-points. In Fig. 10 and 11, on the other hand, the trajectories in auto pilot mode exhibited a better agreement with the circle, thus giving a better tracking of the way-points. In particular, Fig. 11 was able to follow the way-points in their close proximity. As a result, it is concluded that the best choice among the current experiments is ($LIM_ROLL_CD = 2000$, $WP_RADIUS = 90$, $NAVL1_PERIOD = 30$). Therefore this parameter setting will be used for an autopilot flight in future.

Bank angle change in 6th auto flight was shown in Fig.12. According to this graph, the aircraft was successfully able to follow the way-points with a good margin within the value of LIM_ROLL_CD all the time. From this observation, it can be seen that 6th parameter setting is most suitable..

The actual airspeed under the auto-flight and the minimum flight speed calculated based on the structure of airframe in 6th flight are plotted in Fig.13. Also the ground speed, the power consumption, and the throttle rate versus time are shown in Fig. 14, Fig.15 and Fig.16, respectively. The orange straight line represents a minimum flight speed. The step-formed gray lines in Fig. 12-16 show a continuous switching of waypoints.

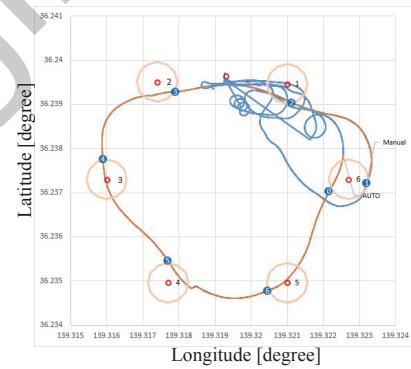


Fig.7 Result of 2nd flight test

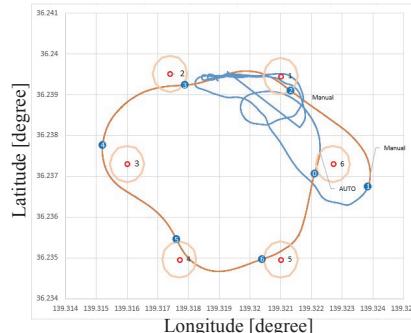


Fig.8 Result of 3rd flight test

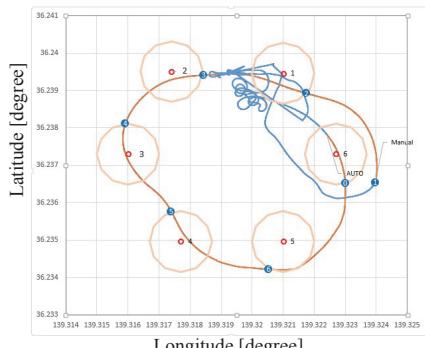


Fig.9 Result of 4th flight test

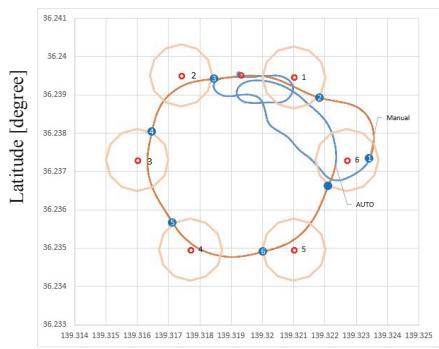


Fig.10 Result of 5th flight test

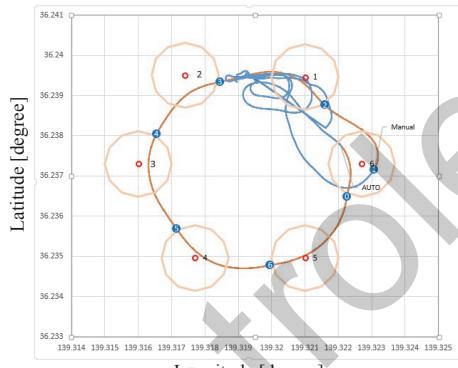


Fig.11 Result of 6th flight test

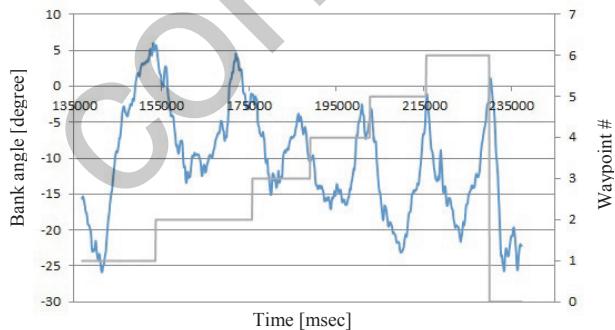


Fig.12 Bank angle versus time for 6th flight

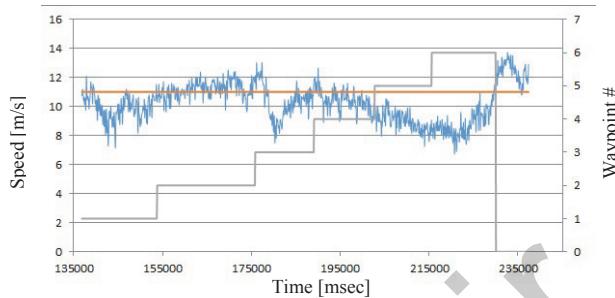


Fig.13 Airspeed (blue) versus time for 6th flight

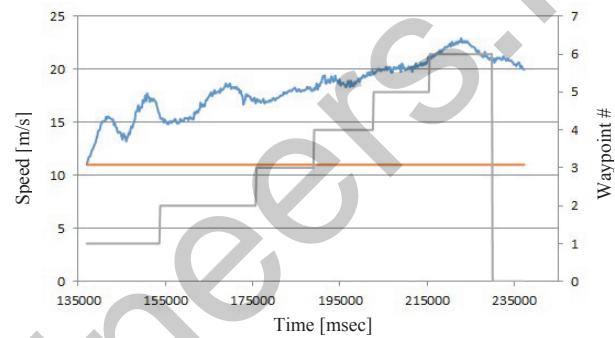


Fig.14 Auto flight ground speed (blue) & ideal speed (orange)

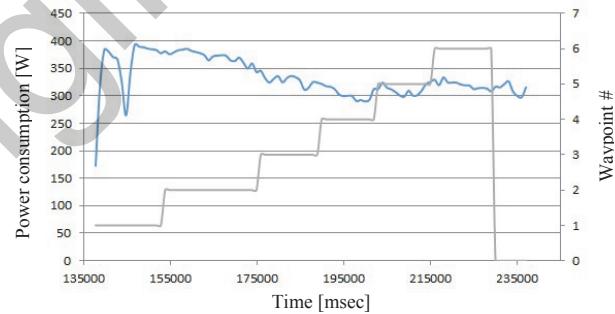


Fig.15 Power consumption (blue) under auto-pilot

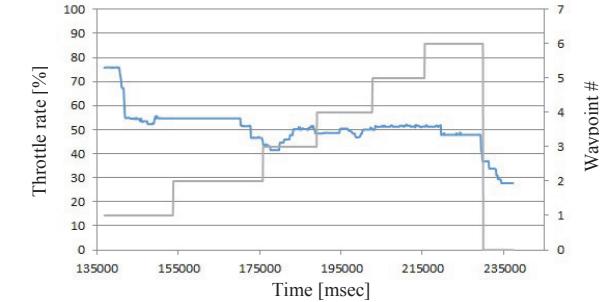


Fig.16 Throttle rate (blue) versus time

V. DISCUSSIONS

The model generated by Datcom+ Pro showed a good agreement with Sunfalcon 1 although some limitations of the software hampered the complete modelling of the aircraft. The

simulation result in altitude tracking also exhibited a reasonable performance while the control gains needed more careful tuning. These results suggest that the combination of Datcom+ Pro, MATLAB[®], and Simulink leads to an efficient development of flight simulator. However, the simulation environment at the current level is not sophisticated enough to be applied to the real aircraft. One possible approach will be to implement the guidance method employed by ArduPilot in MATLAB[®] and Simulink environment.

Regarding the navigation experiments, setting WP_RADIUS small increases the possibility of a missed way-point. Generally speaking, a small WP_RADIUS should be used with a large LIM_ROLL_CD and a small NAVL1_PERIOD, which allows more aggressive maneuvers with an increasing danger of stall. Also LIM_ROLL_CD in Fig.9 was so small that the vehicle could not change the direction quickly enough to reach the fifth way-point. As far as NAVL1_PERIOD is concerned, we chose default value of 30 seconds. This value should be carefully chosen according to the nature of a desired trajectory.

In Fig.12 the bank angle exceeded LIM_ROLL_CD when aiming at the first and fifth target way-point. This was probably caused by the presence of tailwind. Comparing the airspeed in Fig. 13 with the ground speed in Fig.14, about 8[m/s] of speed difference is observed. This observation is also explained by the same tailwind. The bank angle became larger due to the wind blowing against the aircraft wing.

Fig.13 also indicates that the actual airspeed (blue) is maintained at a similar level to the ideal flight speed (orange). This reveals that the current setting of the throttle rate at 50% is a reasonable choice for Sunfalcon1. However, the airspeed shows a sudden drop while aiming at the third way-point despite the throttle rate being maintained constant. A similar observation can be made for the power consumption in Fig.15 as well. A probable cause for this problem is a decrease in motor rotations due to a drop in power sent from ArduPilot to the motor caused by a voltage drop.

VI. CONCLUSIONS

Modelling of Sunfalcon 1 was carried out by using Datcom+Pro. The resulted model was imported into

MATLAB[®] environment and tested for the altitude tracking control. It was confirmed that the result showed a reasonable performance although the model as well as the controller require further sophistication and tuning. In order for the current simulator to be more practical, we plan to implement the guidance method of ArduPilot so that the vehicle response in the simulator is made similar to the actual one.

The flight tests for Sunfalcon 1 were conducted in order to identify an optimal parameter setting. As a result, LIM_ROLL_CD: 2000, WP_RADIUS: 90, NAVL1_PERIOD: 30 yielded the best flight in auto pilot mode among the limited number of test cases. However, more detailed parameter tuning will be needed under varying flight conditions. Design of the Sunfalcon 2 is currently in progress. In parallel to the efforts to improve the current system for Sunfalcon 1, we plan to start the modelling process for Sunfalcon 2.

As pointed out in the previous section, there is a risk of an unexpected drop of airspeed caused by a voltage drop even if the throttle rate is maintained constant. In addition, it is seen that there is a danger of fall accident in case of a strong tailwind especially when the plane speed becomes relatively slow during a take-off or landing situation due to an insufficient lift force. These issues need to be taken into account when we try to develop a fully automated program from a take-off to a landing in future.

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