Navigation, Guidance and Control of Parafoil Recovery System For KIT' Experimental Rocket

Takashi YATOH, Yu HIROKI, Itaru SHIDA
Shinichi SAGARA, Koichi YONEMOTO

Department of Mechanical and Control Engineering, Kyushu Institute of Technology, Fukuoka, Japan
(Tel : +81-093-884-3179; E-mail: yonemoto@mech.kyutech.ac.jp)

Abstract: A small experimental rocket was developed for the rocket launch campaign at La Courtine in France. This rocket has the body length of 2m, weighs about 15kg and can reach to an altitude of about 700m by a solid rocket motor. The parafoil recovery system is deployed at the apogee of the trajectory and guide the rocket to the landing point. This paper described the design, the actual flight results of the onboard NGC (Navigation, Guidance and Control) system using GPS (Global Positioning System). The timer sequence after ignition lets the side door of the body open to eject the drogue chute that immediately draws the parafoil recovery system. After the full deployment, the drogue chute is separated. Once the receiving of signals from four GPS satellites are established for position sensing, the NGC system start to pull the riser of the parafoil recovery system to control aiming directions.

Keywords: Navigation, Guidance, Control, Parafoil, Rocket

1. INTRODUCTION

The team of undergraduate and postgraduate students, who belong to the Department of Mechanical and Control Engineering at Kyushu Institute of Technology, has developed a small experimental rocket to participate in the rocket launch campaign in France this July [1]. The rocket launches were conducted in the military camp of La Courtine that is located in the central region of France. This camp with an area of 6,300ha was founded in 1901 for the shooting training of infantry corps.

This rocket launch campaign, which has been sponsored by the French Association of Planet Sciences and supported by CNES (the French Centre National D'Etudes Spatiales), has a long history since 1962 for promoting university students of aerospace engineering and amateur space engineers by providing safe launch opportunities [2].

What most distinctive, attractive and educational of this campaign is that the teams who participate in the campaign do not compete for ranking, but challenge new technologies by performing their own missions. They can exchange knowledge mutually by internet, and can receive advises concerning basic technologies, design standards and interface document [3] from many specialists of the Planet Science and CNES at any time.

Every year about 20 teams participate in the rocket launch campaign not only from France, but also from other countries. There were teams from Belgium, Brazil, Canada, Germany and Great Britain in the past. This year Space Club Gifu, Space Club Kansai, and the team from Kyushu Institute of Technology gathered in La Courtine from Japan.

2. EXPERIMENTAL ROCKET

The length of the experimental rocket is 2.0m with a mass of 15kg, and is capable to reach an altitude of about 700m (Fig. 1). The body of the rocket consists of five structural sections. A pitot tube, a beacon, a telemetry system and a power supply battery for the NGC (Navigation, Guidance and Control) system are mounted in the nose cone. Two microcomputers, two video cameras and a power supply battery for the servo actuators are mounted in the avionics bay. The parafoil recovery system and the ejection/deployment mechanism are installed in the development system bay. The solid rocket motor is mounted in the engine bay. The extension tube is designed to meet the margin of aerodynamic static stability required by CNES.

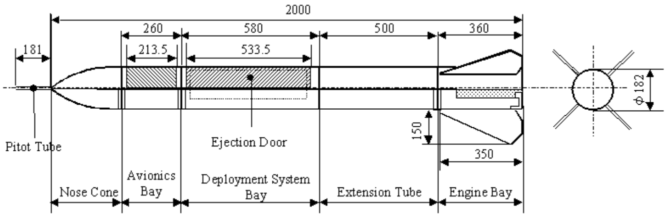


Fig. 1 Dimensions of the experimental rocket

The body cylinder is a monocoque structure made of thin CFRP (Carbon Fiber Reinforced Plastic) tubes reinforced by aluminum alloy flanges and stringers. The nose cone is made of GFRP (Glass Fiber Reinforced Plastic). These five body sections are fastened at each flange by bolts. The solid rocket motor is called "Le Chamois" provided by CNES, which has the initial mass of 3.4kg and the average thrust of 842N (total impulse is 2,043Ns) [4]. The overview of the experimental rocket is shown in Fig. 2.

A commercial power kite is employed for the parafoil recovery system by modifying suspension lines and risers. The aerodynamic characteristics were obtained by the free flight experiments [5]. The drogue chute ejection and the parafoil deployment mechanism were newly designed and tested [6].

Fig. 2 Overview of the experimental rocket

3. PARAFOIL RECOVERY SYSTEM

The mission profile of the rocket launch and recovery is shown in Fig. 3.

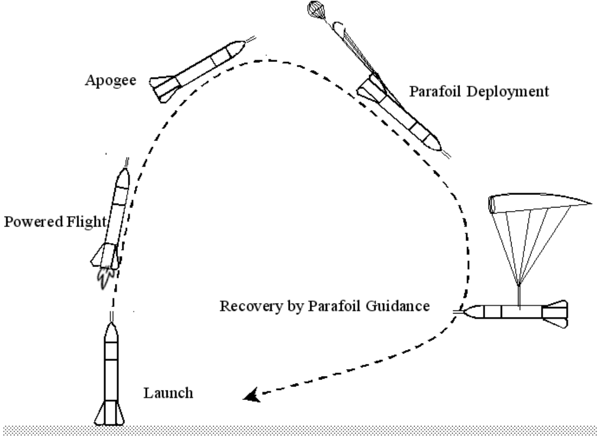


Fig. 3 Mission profile

The solid rocket motor is ignited by a remotely control switch according to the count down of the launch control center of CNES. When the rocket starts to liftoff along the launch pad, the onboard timer begins to count immediately by a signal from the separation switch.

The rocket continues its powered flight about 2.8 seconds and reaches to the altitude around 700m in 10 seconds. At the apogee of the trajectory, the side doors open and a drogue chute is ejected to deploy the parafoil recovery system. When the rocket begin to perform steady flight and the onboard microcomputer recognizes the establishment of receiving signals from four GPS satellites, the calculation of guidance and control starts.

If the parafoil turns the rocket to the right or left direction, the servo motor rolls up the right or left riser respectively to decline the lifting surface (Fig. 4). This operation can be realized by the riser control mechanism as shown in Fig. 5. The rocket is guided by the parafoil to a target position by repeating this operation.

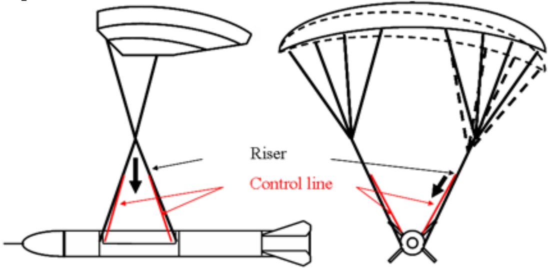


Fig. 4 Turn control of parafoil

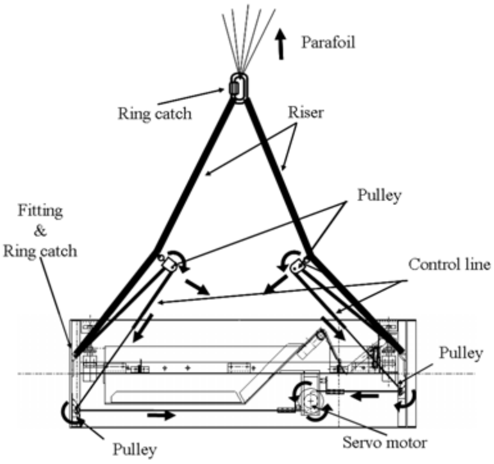


Fig. 5 Riser control mechanism

4. NAVIGATION, GUIDANCE AND CONTROL SYSTEM

4.1 Avionics

The experimental rocket has an avionics that consists of five electronic subsystems (Fig. 6)

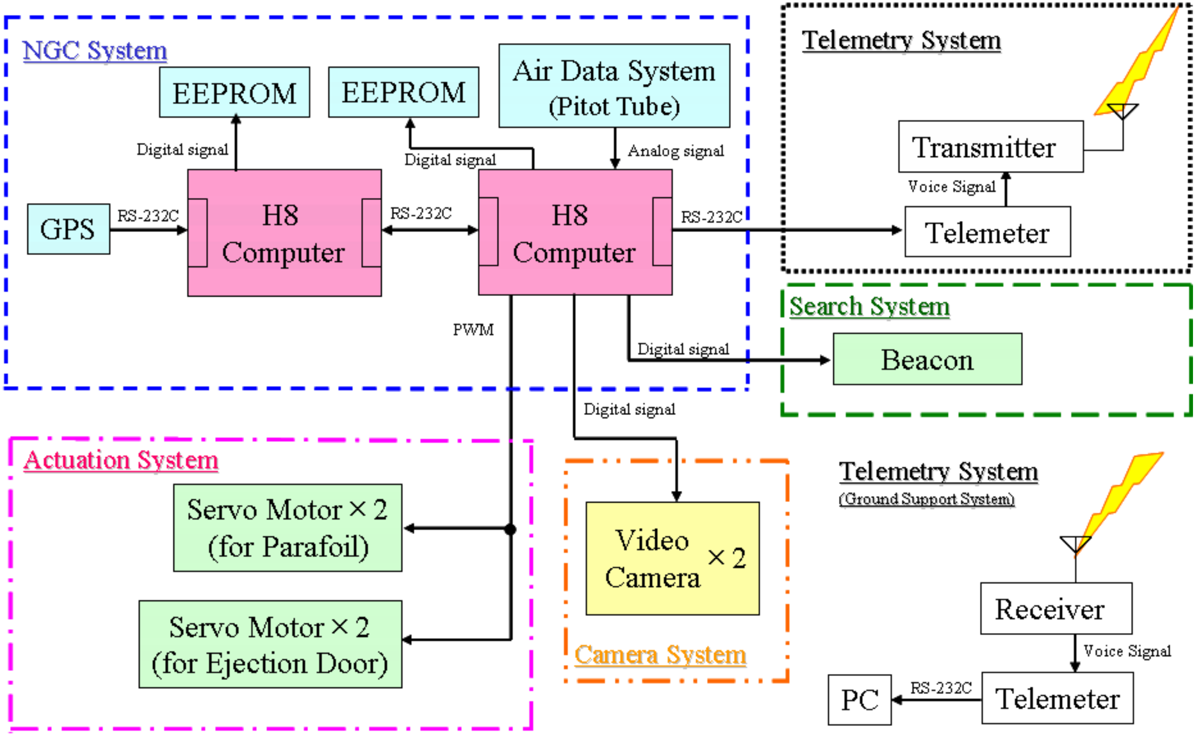


Fig. 6 Block diagram of the avionics

The NGS system consists of two microcomputers (Fig. 7), GPS (Fig. 8), air data system (pitot tube and pressure transducers) and two EEPROMs (Electrically Erasable and Programmable Read Only Memory). The first microcomputer processes the data obtained from GPS, and the second microcomputer performs guidance control calculation based on the GPS data and velocity data obtained from the air data system. The specifications of the microcomputer and GPS are shown in Table 1 and 2 respectivly.

Fig. 7 Microcomputer (H8/3048ONE)

Fig. 8 GPS (geko201)

Table 1 Specifications of the microcomputer (H8/3048ONE)

CPU	Sixteen 10-bit general resisters Maximum clock rete: 25MHz
Memory	ROM: 128 kbytes RAM: 4 kbytes
16-bit integrated	Five 16-bit timer channels, capable of processing up to 12 pulse outputs or 10 pulse
Serial communication interfase (SCI) 2 channel	Selection of asynchronous or synchronous mode Full duplex: can transmit and receive simultaneously
A/D converter	Resolution: 10 bits Eight channels, with selection of single or scan mode
D/A converter	Resolution: 8 bits Two channels
I/O ports	70 input/output pins 8 input-only pins

Table 2 Specifications of the GPS (geko201)

Size	48.3(W)×99.1(H)×24.4(H) mm
Weight	96g
Receiver	Differential-ready, 12 parallel channel
Acquisition time	Approx. 15 seconds (warm start) Approx. 45 seconds (cold start) Approx. 5 minutes (First
Update Rate	1/second, continuous
GPS Accuracy	<15 meters RMS
DGPS (USCG) Accuracy	1-5 meters with DGPS corrections
Velocity Accuracy	3 meters 95% typical with DGPS corrections
Dynamics	0.1 knot RMS steady state
Interfaces	NMEA 0183, RTMC SC-104 and RS-232 for PC interface
Antenna	Built-In

The actuation system, which is commanded by the NGS system, has two servo motors for controlling parafoil risers and two servo motors to open prafoil ejection doors.

The flight information is stored onboard in the EEPROMs. It is simultaneously converted to voice signal and transmitted by the telemetry system to the ground support system of CNES.

4.2 Power supply system

The power supply system has two batteries of 7.2 Volts DC as shown in Fig. 6.

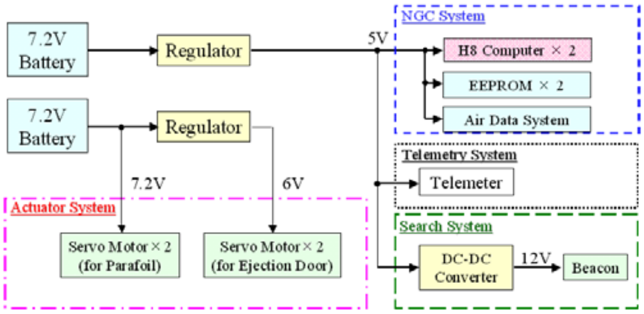


Fig. 6 Power Supply system

The first battery supplies 5V DC through the regulator to the NGS system, the telemetry system and the search system. The second battery supplies 7.2V DC directly to the servo motors used for controlling parafoil risers and regulated 6V DC to the servo motors to open the ejection doors

4.3 Onboard computer program

The onboard microcomputer calculation program is coded in ANSI C language. The flow charts for both the calculation programs that processes GPS data and calculates navigation, guidance control law are presented in the Appendix.

5. GUIDANCE LAW

5.1 Dynamic model

The following simple directional equation of motion is derived when paying attention that the centrifugal force balances with the acceleration of directional displacement:

$$\ddot{Y} = \frac{V_0^2}{R} \tag{1}$$

where Y : directional displacement

V_0 : velocity

R : turning radius

The disturbances in terms of directional displacement and turning radius are defined as follows:

$$\begin{aligned} Y &= Y_0 + y \\ R &= R_0 + r \end{aligned} \tag{2}$$

where y : disturbance of directional displacement

r : disturbance of velocity

The perturbed equation of directional motion can be reduced from Eq. (1) by employing the disturbances defined by Eq. (2):

$$\ddot{Y}_0 + \ddot{y} = \frac{V_0^2}{R_0 + r} = \frac{V_0^2}{R_0\left(1 + \frac{r}{R_0}\right)} \cong \frac{V_0^2}{R_0}\left(1 - \frac{r}{R_0}\right) \tag{3}$$

assuming $|y| << Y_0$, $|r| << R_0$

Separating the steady state equilibrium equation from Eq.(3), the following perturbed equation of motion can be derived:

$$\ddot{y} = -\frac{V_0^2}{R_0^2} r \tag{4}$$

5.2 Directional angle and angular velocity feedback

The relation between the stroke of riser and the turning radius can be described as follows.

$$r = R_l l \tag{5}$$

where l : stroke of riser
R_l : turning radius coefficient in terms of riser stroke

The guidance law, which feedbacks the directional angel to the stroke of riser, is defined by the following equation:

$$l = K_{\Delta\psi}\Delta\psi + K_{\Delta\dot{\psi}}\Delta\dot{\psi} \tag{6}$$

where $\Delta\psi$: directional angle
$\Delta\dot{\psi}$: angular velocity of directional angle
$K_{\Delta\psi}$: proportional feedback gain
$K_{\Delta\dot{\psi}}$: rate feedback gain

In the actual onboard computer program, the directional angle $\Delta\psi$ is calculated from the relation between the velocity vector of rocket and the vector from the present position of rocket to the target position (Fig. 10). The angular velocity of directional angle $\Delta\dot{\psi}$ can be calculated using the previous directional angle in the discrete time frame as follows:

$$\Delta\dot{\psi}(k) = \frac{1}{T}\{\Delta\psi(k) - \Delta\psi(k-1)\} \tag{7}$$

where T : sampling period
k : abbreviation of the discrete time kT

The amount of feedback stroke l in terms of the direction angle $\Delta\psi$ and the angular velocity $\Delta\dot{\psi}$ can be calculated by Eq.(6) and (7).

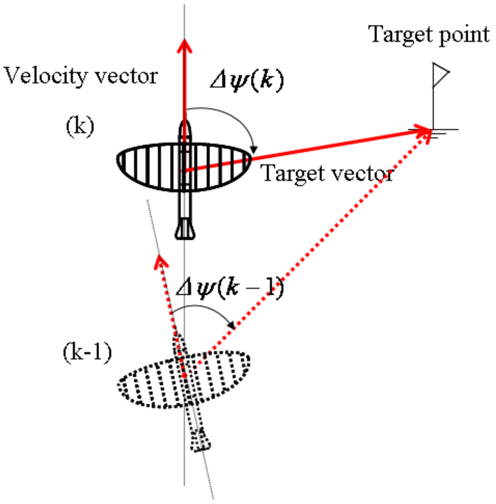


Fig. 10 Definition of the directional angle $\Delta\psi$ and the angular velocity $\Delta\dot{\psi}$

5.3 Calculation of feedback gains

The directional angle and the angular velocity are approximated as follows:

$$\Delta\psi = \frac{y}{L_0}$$
$$\Delta\dot{\psi} = \frac{\dot{y}}{L_0} \tag{8}$$

where L_0 : reference range

Taking account the relation between the stroke of rise and the turning radius of Eq.(5), the guidance law defined by Eq.(6) and the approximation of directional angle and the angular velocity presented by Eq.(8), the perturbed equation of motion Eq.(4) is reduced to the following quadratic equation of motion in terms of directional displacement:

$$\ddot{y} + \frac{V_0^2}{R_0^2}\frac{R_l}{L_0}K_{\Delta\dot{\psi}}\dot{y} + \frac{V_0^2}{R_0^2}\frac{R_l}{L_0}LK_{\Delta\psi}y = 0 \tag{9}$$

The appropriate proportional and rate feedback gains can be calculated by solving Eq.(9).

4. FLIGHT RESULT

The flight profile obtained by the GPS was analyzed and shown in Fig.11. The rocket was launched to the north-east direction with the inclination of 80 degrees by the launch pad. The powered flight phase by the solid rocket motor continued 2.8 seconds and reached the apogee of the trajectory at about 10 seconds after the ignition. The maximum altitude was more than 600m. After the deployment of parafoil recovery system, the rocket decreased its altitude with the sink rate of about 12m/s. The vehicle landed very close to the launch pad with the distance of about 125m. The total flight time was 51 seconds after the ignition of the solid rocket motor.

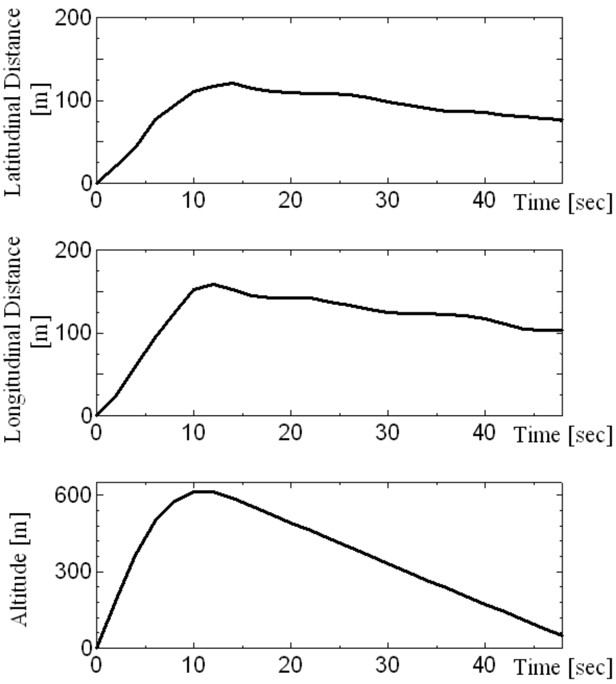


Fig. 11 Flight profile

There were two major different results from what had been anticipated. The first one is the sink rate of gliding flight using the parafoil recovery system. The anticipated sink rate was about 6m/s. The second unexpected result was the landing position, which is far from the target point than anticipated. It can be concluded that the guidance was not performed form the beginning of the parafoil gliding phase.

In order to look into the actual motion of the rocket after deploying the parafoil, the photographs taken from the tracking video camera were investigated. Six photos were displayed in Fig. 12 from the ignition to the time when the rocket begun to glide using the recovery system.

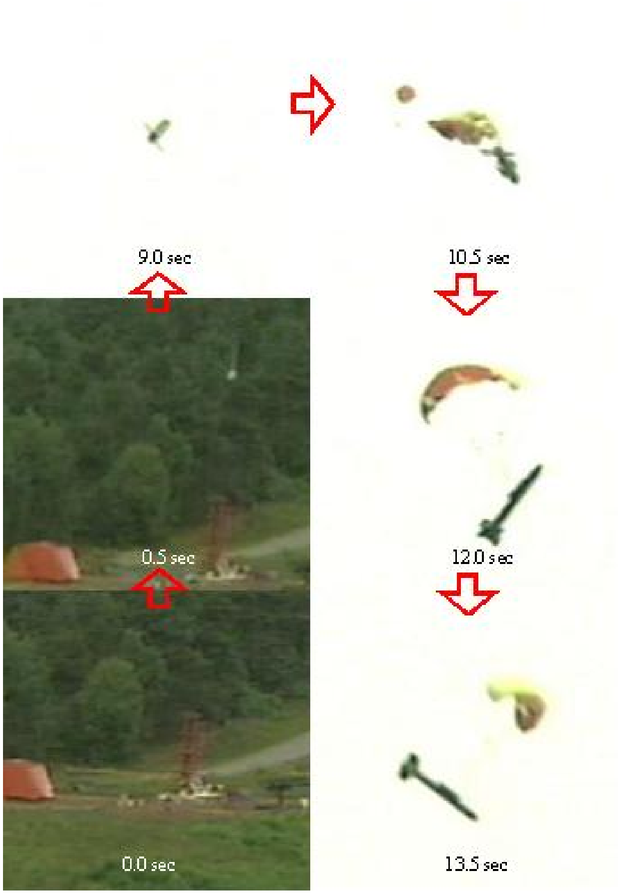


Fig. 12 Photos taken from the tracking video camera

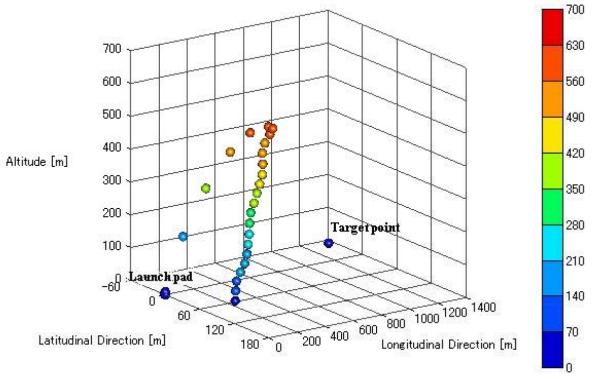
The drogue chute was ejected at 10 seconds after the ignition and it drew the parafoil recovery system at 10.5 seconds. The parafoil recovery system was fully deployed at 11 seconds, and all the sequences of the deployment mechanism were considered successful. But soon after the full deployment of the parafoil, the rocket got into turning in a very high directional angular velocity. Since the onboard NGC system was programmed to start the guidance and control sequence in 10 seconds after the parafoil deployment, it led to a conclusion that this turn had nothing to do with the NGC program. The cause of this turn is considered that any structure of the deployment bay became tangled in the riser of the parafoil recovery system. But further investigation to detect the cause is necessary

The three dimensional flight trajectory and the foot print of the trajectory are shown in Fig. 13.

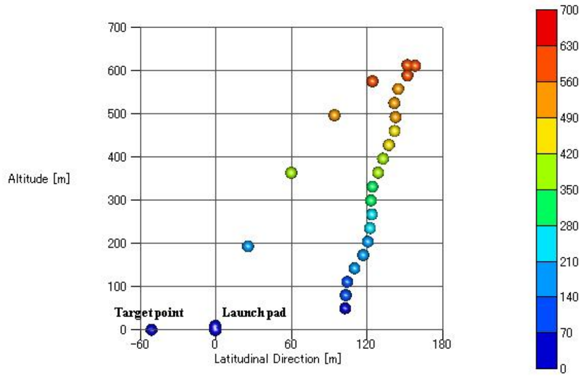
5. CONCLUSION

It is one of the unique challenges for university students to recover the experimental rocket by parafoil recovery system. There are many parafoil experiments led by industries, government institutes or even university to research the feasibility of applying this kind of recovery system to the space vehicle. But most of the experiments have been limited to deploy the parafoil from balloons, helicopters, or aircrafts for the purpose of studying the aerodynamic characteristics or establishing the guidance and control systems. The are few cases to utilize the system in an actual flights.

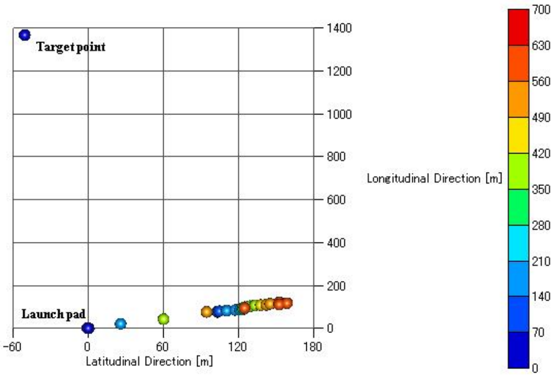
Although there are many subjects remained unsolved, the experience to participate in the rocket launch campaign at La Courtine in France was very fruitful from the aspect not only to know how difficult it is to complete the actual development but also manage the project under difficult circumstances. The students had to understand the interface documents, to consult with specialists, and finally to struggle with the ground tests to be qualified to launch their own rocket. We are still confident to continue our challenges next year.



(three dimensional trajectory)



(two dimensional trajectory)



(foot print of trajectory)

Fig. 13 Flight trajectory

REFERENCES

[1] Yonemoto, K., Sagara, S., Funatu, K., Yatoh, T., Nakamura, T., Hiroki, Y., Fujie, S., Hoshino, M., “The Student Rocket of KIT Flies in the French Sky of the La Courtine,” the 50th Space Sciences and Technology Conference, Kitakyushu, Japan, Nov. 2006.

[2] http://www.planete-sciences.org/espace

[3] “Book of Specifications Single Stage Experimental Rockets (Version 2.1),” Planéte Sciences/CNES (Centre National D’Etudes Spatiales), issued on 15th October, 2004.

[4] “Les Propulseurs des Clubs Scientifiques Spatiaux (Version 5),” CNES (Centre National D’Etudes Spatiales) / ANSTJ, issued on Frbruary, 2002.

[5] Hoshino, M., Oshikata, Y., Kaji, S., Sagara, S., Yonemoto, K., “Evaluation of Flight Characteristics of Recovery Parafoil By Free Flight Experiments,” the 50th Space Sciences and Technology Conference, Kitakyushu, Japan, Nov. 2006.

[6] Fujie, S., Takafuji, H., Tsukinari, Y., Sagara, S., Yonemoto, K., “Development of Parafoil Deployment Mechanism for Small Experimental Rocket Recovery,” the 50th Space Sciences and Technology Conference, Kitakyushu, Japan, Nov. 2006.

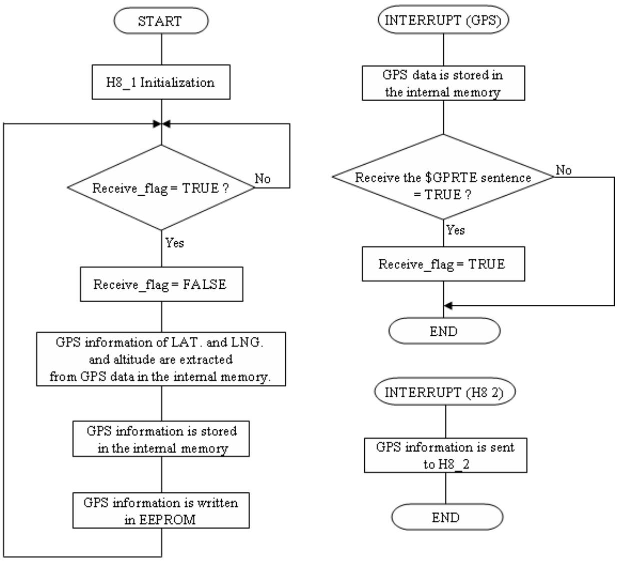


Fig. A-1 Calculation flow chart of the microcomputer H8_1 (GPS data processing)

APPENDIX

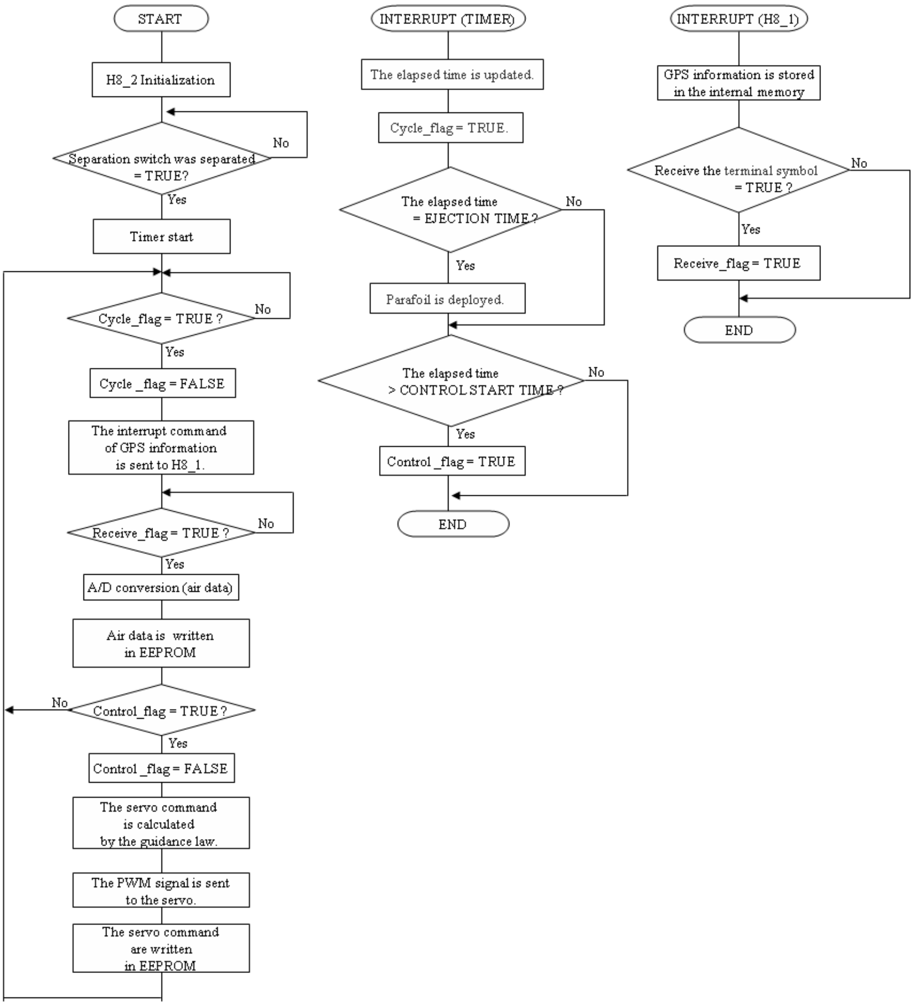


Fig. A-2 Calculation flow chart of the microcomputer H8_2 (navigation, guidance and control law calculation)