JOURNAL OF AEROSPACE COMPUTING, INFORMATION, AND COMMUNICATION
Vol. 4, August 2007

Development of a Real-time Onboard and Ground Station Software System for a UAV Helicopter★

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DOI: 10.2514/1.26408

We report in this paper the development of a real-time software system for an unmanned aerial vehicle (UAV) helicopter, which consists of an embedded computer onboard and a ground station served by a laptop. The software system for the onboard computer performs multiple tasks including data acquisition and measurement, servo driving, automatic flight control implementation, communications and data logging. The system for the ground station gives a flexible graphical interface monitoring the real-time status of the UAV helicopter. We present the frameworks and structures of the onboard and ground station systems. The onboard system employs a framework of multiple task threads with each thread being assigned to perform a specific task. Management and time scheduling for task threads together with the detailed implementation of automatic flight control laws are the main focuses of the onboard software system. A behavior-based architecture is designed to address task scheduling and event disposal for automatic control. A hierarchical and componential structure is developed to integrate multiple control laws and perform various helicopter behaviors. The ground station software system employs a two-layer framework, i.e., data transferring in background and data visualization in foreground. A variety of views are developed to display in-flight data received from the UAV helicopter in different forms including a 3D monitoring panel, which displays real-time data in 3D on the ground station.

I. Introduction

IN recent years, research on unmanned vehicles has gained much attention worldwide.[1] Objects like unmanned aircraft, underwater exploiters, satellites and intelligent robotics are widely investigated as they have potential applications in both military and civil domains. They are developed to be capable of working autonomously without human pilot. Challenge is that they need to deal with various situations arisen in much complicated and uncertain environment, such as unexpected obstacles, enemies attacking and device failures. Besides, they are required to communicate with technical personnel in the ground station. Consideration on a wide range of factors needs to be taken. Control systems for the unmanned vehicles are required to integrate not only basic input-output control laws, but also high-level functionalities for decision making and task scheduling. Software systems for unmanned vehicles are required to perform tasks from hardware driving to the management of device operation, and from traditional input-output control law implementation to task scheduling and event disposal. A number of works have been published in the literature on the system architecture, control method and software implementation for unmanned

Received 09 July 2006; revision received 5 December 2006; accepted for publication 10 July 2007.

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★This work is partially supported by the Defense Science and Technology Agency (DSTA), the Republic of Singapore.

Fig. 1 The HeLion UAV helicopter.

vehicles.[2–8] An introduction of onboard software implementation for a model helicopter is presented by Kottmann,[9] in which onboard tasks such as communications, data logging and control are briefly described. Wills et. al.[3] develop a so-called open control platform (OCP) with reconfigurability and interoperability for complex dynamic systems and present a demonstration prototype of simulation platform for an unmanned helicopter based on the common object request broker architecture (CORBA). A practical solution of software implementation for a fixed-wing UAV is given by Jang and Tomlin,[10] which uses inter-process communications and synchronization to schedule onboard tasks and uses OCP[3] for ground station software. Nevertheless, there is still much work left to explore new technologies of software implementation for unmanned vehicles.

In this paper, we aim to develop a comprehensive software system that can be used to serve as a platform for modeling and implementation of automatic flight control for a real UAV helicopter, which consists of a small-scale basic helicopter with all necessary accessories onboard and a ground station served by a laptop. Figure 1 shows our UAV helicopter, HeLion, developed at the National University of Singapore. The basic helicopter is about 1.41 meter in length and 4.85 kilogram in weight. An embedded computer system is attached at the lower portion of HeLion. The onboard system is composed of a PC/104 computer (CRR3-650, Lippert), an inertial measurement unit (IMU) (NAV420, Crossbow), a data acquisition board (DIAMOND-MM-32-AT, Diamond), a sonar chip (UPK 500, SNT SENSORTECHNIK AG), a wireless communication board (IM-500X008, FreeWave), a set of servo drivers (HBC101, Pontech), and other necessary components.[11]

The automatic flight control system is directly implemented on the onboard system. During flight tests, the IMU, sonar and data acquisition board collect measurement signals of current state of the UAV helicopter. The output signals of these devices are then utilized to generate automatic control signals to drive appropriate servo motors. The onboard software system is built to be capable of performing multiple tasks including hardware driving, device management, automatic control, communications and data logging. It is also to realize multiform control laws and perform various flight actions such as hovering, lifting, forward and backward flying. Our software framework offers good flexibility and extensibility for new modules and control functionalities. The ground station laptop is equipped with wireless modem, which receives data from and sends commands to the HeLion onboard system. Another function of the ground station is to provide a graphical user interface helping users monitor and command the UAV helicopter.

The onboard software system is developed using a real-time operating system, *QNX Neutrino*, which provides reliable support for high precision timer and synchronization operation. The ground station software system runs on a commercial operating system, *Windows XP Professional*, which offers an excellent environment for developing graphical user interfaces. A framework of multiple threads is employed for the onboard system to perform multiple tasks, i.e., to operate hardware like the IMU, data acquisition board and servo system, to log all kinds of data in flying process, to communicate with the ground station, and to implement automatic control algorithms. Each thread performs one specific task. Time table for both software and hardware processing is designed and tested. To implement automatic control, a behavior-based architecture is employed. In such architecture, the operation of the helicopter is organized in a variety of behaviors. A hierarchical and componential structure is used to execute these behaviors and to integrate multiple control algorithms. Our ground station system has two layers, namely, data transferring in background and user interface in foreground, which consists of a curve view of data in coordination style and a 3D view simulating the attitude and motion of the actual helicopter.

The content of this paper is organized as follows. Section II presents the onboard software system, in which the implementation of task management and automatic control are given together with some source codes. The framework and implementation of the ground station software are documented in Section III, in which the graphical interface and 3D view development are discussed. Section IV addresses a variety of practical issues involved in the process of software development together with some actual flight test results. Finally, we draw some concluding remarks in Section V.

II. Onboard System

We present in this section the development of the framework of the onboard system, which contains a number of task blocks dealing with specific onboard devices. We demonstrate how these tasks are managed and scheduled through a mechanism of multiple threads, and how the automatic flight control is implemented.

A. Framework of Onboard System

The framework of the onboard system is depicted in Fig. 2. The software part consists of several blocks, each of which is designed for a specific device and task. The IMU block interacts with the inertial measurement unit and retrieves its measurement data. The NAV420 of Crossbow is a GPS aided unit which is capable of providing both GPS signals and inertial measurement.[12] Its outputs include positions (latitude, longitude and altitude), velocities, attitude, angular rates, acceleration and magnetic field. The IMU works at a frequency up to 100 Hz, which means that the measured data are read at a cycle of 10 ms. The DAQ block is to read additional information from the data

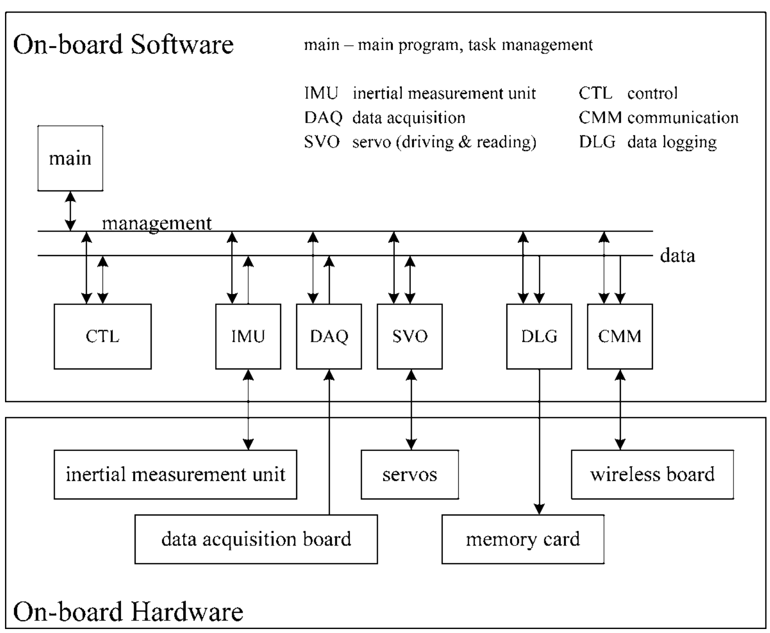


Fig. 2 Framework of the onboard system of the UAV helicopter.

acquisition board, such as the rotating speed of the main rotor, the liquid level of the fuel box. The CTL block is to implement automatic flight control laws. This is the only block that does not interact with hardware, but with the IMU block and the SVO block. During flight tests, it reads the state of the helicopter from global shared data from the IMU and performs calculation of control algorithm to generate automatic control signals that drive the servo motors. The upper level tasks such as navigation, task scheduling and plan interpretation can also be integrated into this block. The SVO block is the servo driving system, which is to drive the helicopter servos and read servo position. Our helicopter servos include aileron servo (roll control), elevator servo (pitch control), auxiliary servo (collective control) and rudder servo (yaw control). The CMM block is for communications between the onboard system and the ground station terminal. A duplex wireless board of bandwidth 115,200 bit per second is used to download in-flight data of helicopter and upload user commands. The DLG block performs data logging, which is usually considered as a background task saving all data including measurements and inner states during operations. A 256 M compact flash card is employed as the storage media for the onboard system. We do not choose hard disk because of its size and its vulnerability against vibration which is unavoidable on the helicopter. The main block is to manage all tasks. Mechanism of its management and scheduling will be discussed in detail in the next subsection. Exchange of data between blocks is accomplished by a global shared data scheme, in which all data are centralized.

B. Task Management

The task management of all blocks is implemented using the *QNX Neutrino* real-time operating system, which supports timers of high-frequency up to a nanosecond level and provides a variety of system functions for synchronization.[13,14] These characteristics are crucial for implementing automatic control laws that require fast responses.

A scheme of multiple threads is employed to implement these tasks. Every task is performed in a separate thread, called task thread. They are periodically activated at a pre-set rate. In every period, these task threads are scheduled to run in a designed order through a mechanism of synchronization. The mechanism prevents the main thread and other threads from blocking each other. Processing times for different tasks are different. A scheduling table for both software and hardware processing is designed based on the statistics of test data.

Task scheduling is performed in the main thread. At every period, the main thread sends pulse messages to all task threads one after another. The pulse message acts as activating signal for the task thread. It wakes up the task thread to perform work. Programs are developed as follows to implement such mechanism.

```
main program
  initialize task threads
  initialize timer
  loop {
    wait for timer signal
    read user command
    if command is for exit, exit loop
    send an activating pulse to task thread 1
    wait some time for task 1 accomplishment
    send an activating pulse to task thread 2
    wait some time for task 2 accomplishment
    …
    send an activating pulse to task thread n,
    wait some time for task n accomplishment
  }
  send an exit pulse to task thread 1,
  send an exit pulse to task thread 2,
  …
  send an exit pulse to task thread n.
  exit main program
task thread
  loop {
```

wait for a pulse
if pulse is for exit, exit loop
do work
…
set notification of accomplishment
}
exit task thread

A timer is used to schedule the execution process of the main program. The timer emits a pulse signal at every specific period to activate task processing. The main program contains a waiting and processing loop. In the loop, the main program waits for a pulse signal from the timer. It keeps idle until a timer signal is captured. Once the signal is captured, the user command is read and executed. The loop will be terminated if an exit command is received. The main function of every cycle is to send activating pulses to task threads in a pre-scheduled order. After all the scheduled task threads are executed, the program returns to the loop and waits for the next timed pulse signal. The frequency used in our system is about 20 ms per cycle. When an exit command arrives to terminate the loop, the main program will send exit pulses to every task thread scheduled.

The executions of task threads are carried out in a similar fashion. In the entrance of a task thread loop, it waits for a pulse signal from the main program. Once an execution signal is received, all subsequent steps scheduled in the thread are then executed. The loop is terminated when an exit pulse is received from the main thread. After the thread is successfully processed, a notification signal will be sent to the main program loop. The main program then proceeds to process the next task thread. The waiting scheme for each task thread gives the thread exclusive occupation of the CPU resource and prevents the main program from terminating the thread when it is running.

The *QNX* library of threads, messages and synchronization are used to implement the task management of our system. Table 1 lists various functions[14] used in the program. The overall management of these task threads is described in Fig. 3. The execution structure is like a lotus. Each single node stands for a task thread. The center part stands for the main thread. Solid arrows in the figure stand for the task thread activation or notification of accomplishment and indicate the exchanges of the processes. Dotted round arrows in the center of the task nodes denote the direction of processing. Along the processing direction of main thread, task threads are activated one after another. The execution order is designed using common senses. Tasks such as the IMU and DAQ threads, which are to retrieve measurement data used for implementation of automatic flight control laws, are placed at the beginning of the sequence. They are followed by the CTL thread for automatic flight control, which involves in manipulating control algorithms and generating control signals for the servo part. After that is the servo driving task thread. The communication and data log task threads are scheduled at the end of the sequence to respectively transfer and save the in-flight data and information of the helicopter. The implementation detail of activation and notification is depicted in the diagram on the right hand side of Fig. 3. The activation is implemented by a pair of messages (send/receive calls) and the notification is implemented by a pair of condition variables (signal/wait calls).

In every cycle, each thread needs a period of time to process its task. Different threads need different time durations for processing both software and hardware tasks. In our system, the inertial measurement unit is operated through

Table 1 QNX run-time functions.

Function	Description
pthread_create	create a new thread
pthread_mutex_lock	lock a mutex object
pthread_mutex_unlock	unlock a mutex object
pthread_cond_signal	signal a condition variable and unblock threads waiting for it
pthread_cond_wait	wait for a condition variable and block the calling thread on it
timer_create	create a timer
timer_settime	set property of a timer (starting time, repeating interval, . . .)
MsgSendPulse	send a pulse to a channel
MsgReceivePulse	receive a pulse from a channel
TimerTimeout	set expiration time for waiting function

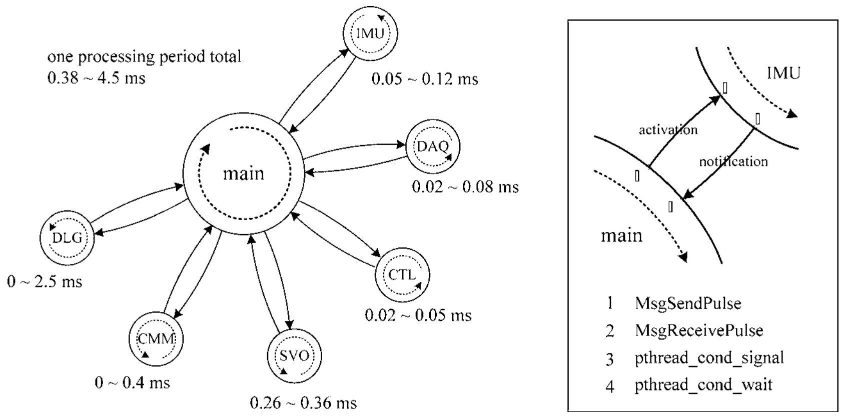


Fig. 3 The management of the main thread and the task threads.

a serial port. It takes about 10 ms to process a command requesting for data and to send the requested data back. The servo task thread has similar operations. Positions of servos need to be read every turn. It takes about 8 ms to process requesting commands. For these threads, the read operation in software has to wait for a period of time to get the response from the corresponding hardware device after the requesting command is sent. The data acquisition task thread collects data through the data acquisition board, which sends data back immediately. The control thread is a pure calculation task. Time consumption for processing such a thread depends on the complexity of control algorithms and the speed of the CPU. For the communication thread, time consumption depends on the data flux to the ground station and the bandwidth of the wireless modem. As mentioned earlier, the maximum bandwidth of the wireless modem installed is 115200 bit per second, i.e., it takes about one second to transfer 14 kilo bytes of data. The wireless modem is relatively a slow processing device that cannot afford massive data transferring. Considering its capacity, the communication thread transfers data to the ground station about once every fifty cycles, i.e., once per second. The time consumption of the data logging thread depends on the size of data to be saved and the speed of the storage device used. To improve efficiency, the data logging task thread is scheduled to store data while they are piled up to a certain volume. In our system, the in-flight data of the UAV helicopter are stored once every fifty cycles, the same as the communication thread.

Figure 4 gives an illustration of the time table for both software and hardware processing in our system. The processing cycle is set to 20 ms. The stack on the left describes software processing in one cycle, which totally consumes about 0.38∼4.5 ms. Hardware processing runs in parallel with its software counterpart. As shown in the figure, the inertial measurement unit and the servos begin to process after their requesting commands are issued. The software part does not stop and wait for hardware processing. It continues on processing other tasks scheduled in

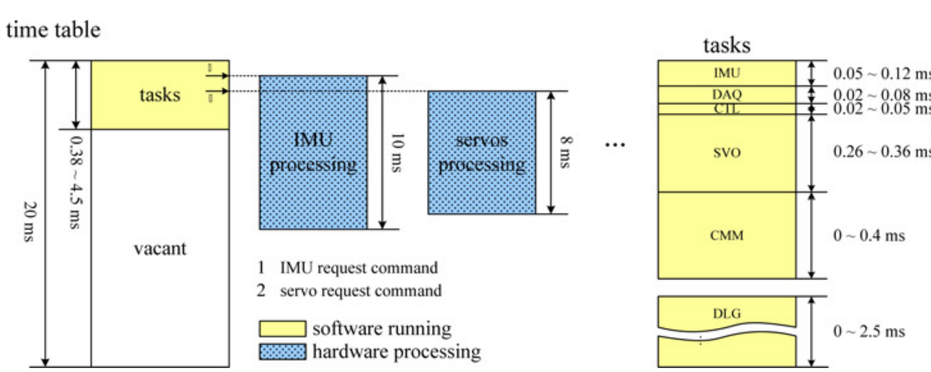


Fig. 4 Time table for the processing task threads.

the sequence. When the requested data are ready, they will be read in next cycle. After all the tasks are executed (in about 4.5 ms), a vacant time block is left in the software, which can be used for additional features developed in the future. It is also ideal for the overall software system to keep a low working load of the CPU. The detailed description of software processing is depicted by the stack on the right hand side of Fig. 4, where a list of time consumptions is given for all task threads.

C. Implementation of Automatic Control

With a properly designed automatic controller, the aircraft is able to perform some automatic flight patterns such as lifting, forward or backward flying in a constant velocity, and flying along a pre-specified trajectory. To perform a complete task, it is needed to combine a series of these flight patterns or behaviors. For example, a reconnaissance task may be accomplished by a series of flight actions such as lifting, flying to the target location, hovering, photo-taking and returning. A behavior-based architecture is employed to organize various behaviors or flight patterns in a plan. In the behavior-based architecture, operation of the unmanned helicopter is composed of behaviors, which form the basic units of the agent operation. The accomplishment of a task is made up of execution of a series of behaviors. Plans are established to define the organization of these behaviors. A plan consists of a set of basic units, which the UAV helicopter needs to perform, and events upon which these behaviors are triggered. In short, the plan defines a schedule, which specifies the executing time and order of a set of behaviors. Interested readers are referred to a recent work[15] for a more detailed description of the behavior-based architecture.

The behavior-based architecture of our UAV helicopter system is given in Fig. 5. It consists of two parts, the task scheduling block and the control system block. The scheduling block hosts plans for the helicopter. They are described by diagrams with nodes and lines. Each node represents a specific behavior or a sub-plan and each line represents an event. Events trigger switching from one behavior to another. Events can be generated through the following three sources: (1) the surrounding environment or hardware situation, such as arisen obstacles, detected targets and hardware fault; (2) the judgment on flight state, such as the achievement of control objectives; and (3) a user command. The task scheduling block therefore employs an event-driven mechanism. Based on retrieved information of the state and environment, it judges what event had happened and what behavior should be executed in response to the event according to predefined plans. The determined behavior is dispatched to the control system block and executed. The task scheduling block is a decision maker or commander, and the control system block is an executor. Actually, the task scheduling block replaces the role of the human pilot in manned aircraft.

The control system block is for the execution of behaviors, i.e., to drive the UAV helicopter to complete certain flight actions specified by the behaviors. Each behavior is implemented for a particular control mechanism. The overall control system is designed in a componential and hierarchical structure to integrate multiple control laws and implement behaviors of different levels. It contains a collection of control components with each component being programmed for a specific control law to generate control signals based on internal information and measurement signals received. The overall control system is thus implemented with one or a combination of these components.

These control components can be classified into two levels in our design, the inner loop and the outer loop. The inner loop is designed for attitude control and for driving the helicopter to a steady state. The outer loop is for navigation, e.g., to guide the UAV helicopter flying to a specific target location in a desired orientation or along a designated trajectory. Multiple components are allowed in each level to implement different control laws and to perform one control task with different parameters and performance in different situations or for different purposes. In our system, there is more than one component in both the inner-loop level and outer-loop level. Some behaviors have to be performed by executing multiple components. Usually, the execution of the outer-loop components requires the cooperation of the inner-loop components.

However, it should be noted that the proposed behavior-based architecture is different from the traditional behavior-based architecture[16,17,18], which was originally proposed for robotic systems. In the traditional setting, the behaviors are considered as integral control. In this paper, the behavior is much like a concept standing for an action, a kind of operation of an agent, and the control system is considered as a pure behavior executor although it can be hierarchical as well. Another note is that the scheduler is clearly separated from the control system rather than being one higher level in the control system as the sequencer in the traditional behavior-based architectures.

As a practical example, Figure 5 shows the structure of the control system we developed for our UAV helicopter. Three different types of control laws are implemented for the inner loop including state feedback control, state

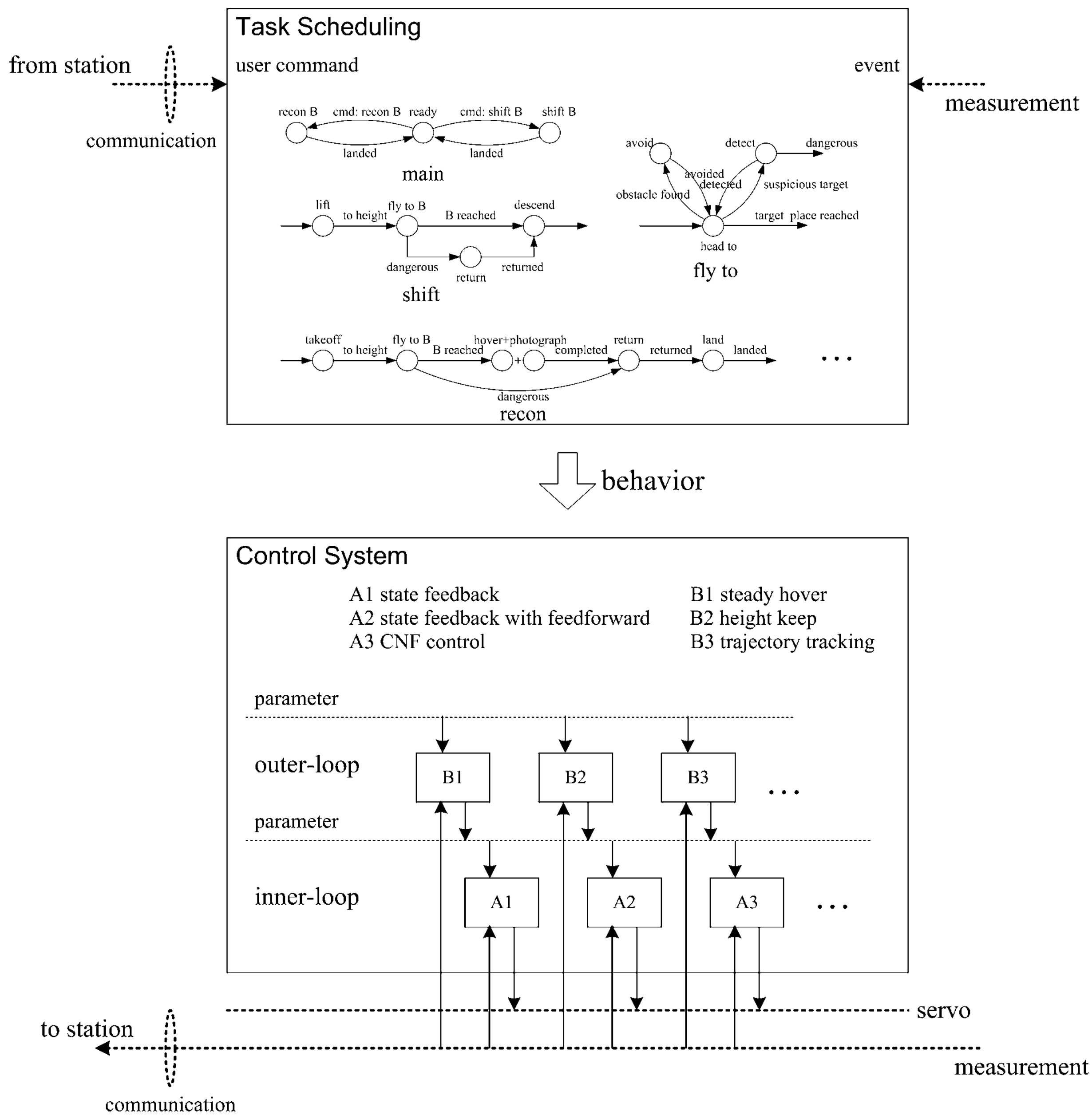


Fig. 5 Behavior-based architecture.

feedback control with feed-forward and composite nonlinear feedback (CNF) control. They are implemented in components labeled A1, A2 and A3. In the outer-loop level, three components labeled B1, B2 and B3 are respectively designed to execute different operations, position and direction holding, height keeping and trajectory tracking. The outer-loop components need to work together with the inner-loop components. When the outer-loop is activated, it does not send control signals directly to the servo system. Instead, it generates a set of control settings or parameters for the inner-loop components. Descriptions of these components including their functions and parameters are listed in Table 2.

In Table 2, $\mathbf{u} = (\delta_a, \delta_e, \delta_u, \delta_r)$ contains the control inputs for aileron, elevator, collective and rudder, respectively. $\mathbf{x} = (u, v, p, q, \phi, \theta, a, b, w, r, r_{fb})$ is a collection of dynamical state variables of the helicopter identified in

Table 2 Control Components.

ID	Function	Description	Parameter
A1	$\mathbf{u} = \mathbf{F}\mathbf{x}$, $\mathbf{x} = \mathbf{x}_{\text{real}} - \mathbf{x}_{\text{ref}}$	state feedback	$\mathbf{x}_{\text{ref}}$
A2	$\mathbf{u} = \mathbf{F}\mathbf{x} + \mathbf{G}\mathbf{v}$	state feedback with feed forward	$\mathbf{v}$
A3	$\mathbf{u} = \mathbf{F}\mathbf{x} + \mathbf{G}\mathbf{v} + \rho\mathbf{B'P}(\mathbf{x} - \mathbf{H}\mathbf{v})$	CNF	$\mathbf{v}$
B1	$\mathbf{V_g} = \mathbf{k}(\mathbf{X} - \mathbf{X_c})$, $r = k_\psi(\psi - \psi_c)$	position and direction holding	$\mathbf{X}_c$, ψ_c
B2	$w = k_z(z - z_c)$	height keeping	z_c
B3	$\mathbf{V_g} = \mathbf{k}(\mathbf{X} - \mathbf{X_c}(t))$, $r = k_\psi(\psi - \psi_c(t))$	trajectory tracking	$\mathbf{X_c}(t)$, $\psi_c(t)$

modeling process and controller design.[19,20,21] u, v and w are, respectively, the velocity of the helicopter along the coordinate axes of its body frame. ϕ, θ and ψ are, respectively, the roll, pitch and heading angles of the helicopter with respect to the North-East-Down (NED) frame. Likewise, p, q and r are the roll, pitch and yaw rates of the helicopter along the axes of the body frame. Finally, a and b are longitudinal and lateral flapping angles of main rotor, and r_{fb} is an internal state for the yaw channel model. The identified model is verified by actual flight data collected from flight tests[21]. The component A1 is for a state feedback control law, in which $\mathbf{F}$ is a static state feedback gain matrix. A2 implements a feedback control law with a feed-forward term, in which $\mathbf{G}$ is the feed-forward gain matrix, and the vector $\mathbf{v} = (u,v,w,r)_c$ contains a number of parameters representing the target reference for the inner-loop components. A3 is created for the CNF control,[22,23] in which $\mathbf{B}$ is the identified input matrix of the helicopter model. $\mathbf{P}$ and $\mathbf{H}$ are designed constant matrices and ρ a nonlinear function matrix. The function of B1 is to hold the helicopter at a desired position with a desired direction, in which $\mathbf{X} = (x, y, z)$ denotes the position of the helicopter and the subscript 'c' indicates the reference (objective) value, and furthermore, $\mathbf{V}_g = (u, v, w)_g$ is the velocity of the helicopter with respect to the ground frame. Control laws for the outer loop are normally proportional control, which are rather simpler as compared to the inner loop. B2 is to implement height keeping for general cruising, where z is the negative of the actual height of the aircraft. B3 is for trajectory tracking. A trajectory is represented by $\mathbf{X}_c(t)$ and $\psi_c(t)$ where $\mathbf{X}_c$ is the expected position and ψ_c the expected heading angle. The control function of B3 is almost the same as that of B1 except that the former is dynamic whereas the latter is static. We also note that the outputs of the outer-loop components are transformed into target reference parameters for the inner-loop components. For example, the output of B1 is the velocity $\mathbf{V}_g$ and the yaw rate r. $\mathbf{V}_g$ is in the ground frame and can be transformed to the body frame. Then, the values of the velocity in the body frame and the yaw rate are assigned as the reference parameters ($\mathbf{x}_{\text{ref}}$ or $\mathbf{v}$) for the inner-loop components.

Behaviors of the helicopter are executed through the combination of these components. Table 3 shows a list of some behaviors implemented in our system. The behavior is implemented by combining activated components with necessary parameters. For example, the hovering behavior (H1) is to keep the UAV helicopter in a hovering state, which is implemented by combining components B1 and A1. The outer-loop control is employed to hold the helicopter steady in a specific position. The target position $\mathbf{X}_c$ and heading angle ψ_c are the parameters of H1, which drives B1 and which in turn generates a reference state for A1. The behaviors for lifting and descending (H2 and H3) can be

Table 3 Behaviors.

ID	Behavior	Parameter	Components	Parameter
H1	Hover	Position $\mathbf{X_c}$, Direction ψ_c	B1, A1	B1: $\mathbf{X_c}$, ψ_c
H2	Lift	Lift-up Velocity w_c	A2	A2: $\mathbf{v} = (0, 0, -w_c, 0)$
H3	Descend	Descending Velocity w_c	A2	A2: $\mathbf{v} = (0, 0, w_c, 0)$
H4	Straight Flight	Straight Velocity u_c, Height h_c	B2, A2	B2: $z_c = -h_c$ A2: $\mathbf{v} = (u_c, 0, 0, 0)$
H5	Turning Flight	Circle Radius R, Circle Rate r_c, Height h_c	B2, A2	B2: $z_c = -h_c$ A2: $\mathbf{v} = (Rr_c, 0, 0, r_c)$
H6	Free Flight	Velocity (u_c, v_c, w_c) , Yaw rate r_c, Height h_c	B2, A2	B2: $z_c = -h_c$ A2: $\mathbf{v} = (u_c, v_c, w_c, r_c)$
H7	Trajectory Tracking	Reference Trajectory $\mathbf{X_c}(t)$, $\psi_c(t)$	B3, A2	B3: $\mathbf{X_c}(t)$, $\psi_c(t)$

implemented by a single inner-loop component A2 by setting either lifting or descending velocity parameter w. Three height-keeping flying behaviors (H4–H6) are implemented by the combining B2 and A2. The outer-loop component B2 is to keep the flight height. The inner-loop component A2 is to control the forward velocity, lateral velocity and yaw rate. The trajectory tracking behavior (H7) is implemented by components B3 and A2. The interactions between the inner- and the outer-loop components are through parameters such as (u, v, w, r). For example, a circle flight behavior can be implemented by combining (B2, A3) or (B2, A1). Some behaviors are homological, such as lifting (H2) and descending (H3), straight flight (H4), circle flight (H5) and free flight (H6).

A detailed diagram of mechanism of the behavior execution is presented in Fig. 6. Two types of behaviors are given for illustration. The first behavior H1 is a hovering action implemented by two levels of control by components A1 and B1. A1 is a state feedback control component upon an equilibrium point referred as $\mathbf{x}_{\mathrm{ref}}$, and B1 uses an outer-loop feedback control to control the position and heading angle. The behavior is first translated into an activation list, which contains the activation state of all necessary components and parameters. The first column in the list in Fig. 6 indicates the activation state of each component, 1 for on and 0 for off. Parameters for each component are listed in the second column. For inactive components, parameters are set to zero. Parameter for A1 is the reference state. The values of u^*, v^*, w^* and r^* are determined by the upper-level component B1. The activation list then is implemented as the middle part of Fig. 6 shown. Grayed components represent for inactive ones. Active components A1 and B1 cooperatively implement the overall control action. The output of B1 dynamically set the parameter for the lower-level component A1. The superscript '+' indicates parameter directly inherited from behavior parameter.

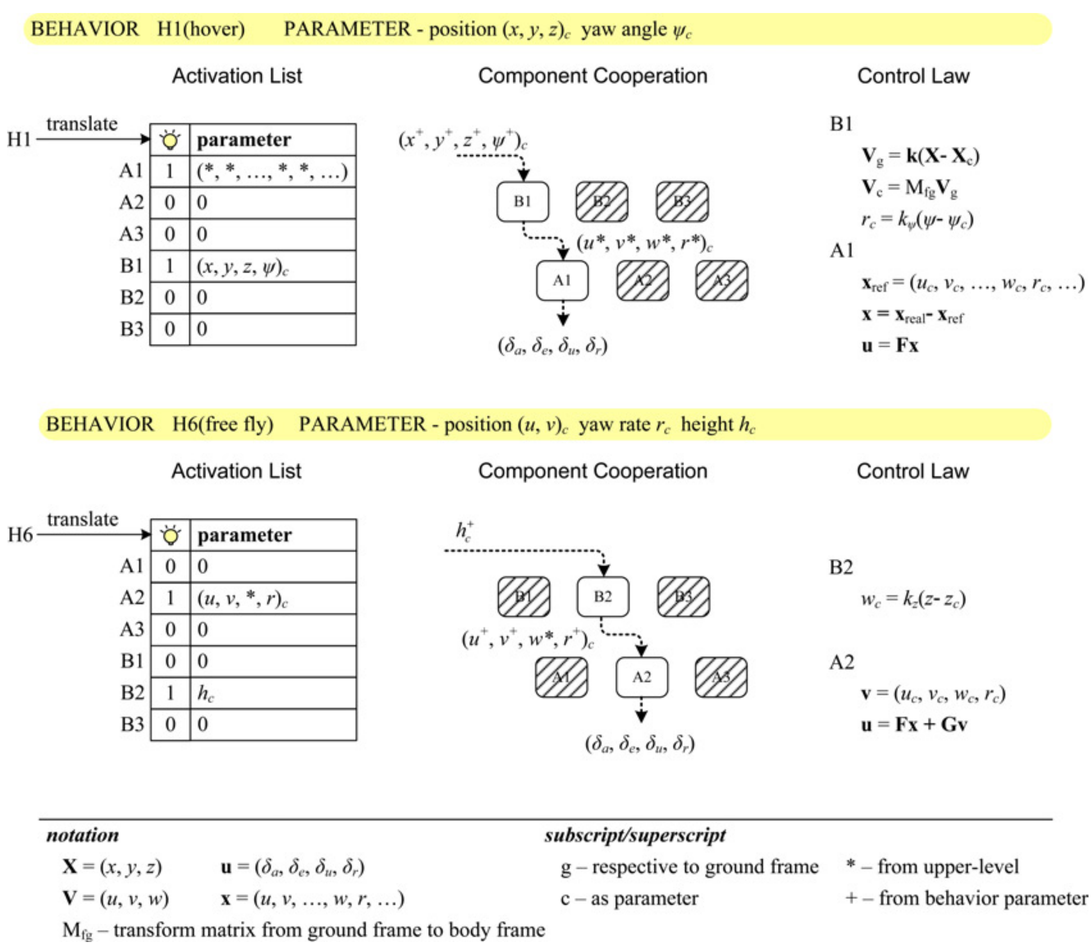


Fig. 6 Diagram of behavior execution.

The superscript '*' indicates parameters determined by the upper-level component. Control laws of B1 and A1 are given in the right hand side of the figure. The outer-loop control (B1) performs position and heading angle feedback. The position error is turned to velocity in the ground frame and transformed into values in the body frame. The error of the heading angle is transformed into yaw rate. The obtained velocity and yaw rate are then used by the inner-loop control (A1) as the target reference. The behavior H6, in the second portion of the figure, is to perform a height-keeping flight with a specific forward velocity u_c, a lateral velocity v_c, a yaw rate r_c and a flight height h_c. It is translated to an activation list in which A2 and B2 are set to be active. Parameters u_c, v_c and r_c are directly sent to the lower-level component A2 and h_c is passed to the higher-level component B2. The parameter w_c for A2 is dynamically determined by B2. Control laws of A2 and B2 are highlighted in the figure as well. A2 performs a state feedback control action with a feed-forward term. B2 performs a negative feedback using the error between the actual height of the aircraft and the target reference.

Lastly, we note that all of control implementations presented above reside in control task thread (CTL) in the software framework. Like other task threads, it is called to perform task scheduling, behavior execution and control law calculation in every processing cycle. In each cycle, the program is executed as in the following.

stage 1: look up plan

check all events linked to current node
if any event occurs return corresponding behavior and parameters
else return null

stage 2: translate behavior to activation list

if behavior equals H1, set flag A1 and flag B1 on, set corresponding parameters
else if behavior equals H2, set flag A2 on, set corresponding parameters
else if behavior equals H3, . . .
. . .
else do nothing; //behavior is null, doing nothing on flag and parameters, keep current control

stage 3: execute behavior

if flag B3 is on, run B3 function
if flag B2 is on, run B2 function
if flag B1 is on, run B1 function
if flag A3 is on, run A3 function
if flag A2 is on, run A2 function
if flag A1 is on, run A1 function

In the first stage, it looks up the plan, and checks events linked to the current node, as display in the diagram. Occurrence of event is judged on information retrieved from GPS sensor, camera, etc. If a certain event occurs, it will return a corresponding behavior triggered by this event. Otherwise, no action is taken. In the second stage, the behavior is translated into a corresponding activation list with necessary parameters. The activation state is controlled by flags for control components. For example, the behavior H1 activates the flag A1 and flag B1 to be turned on. If no behavior is generated from the previous stage, no action will be taken on flags and parameters, which means that the system is performing the current control function. In the third stage, the program enters a series of control component executions. Functions of the control components are run or skipped according to the states of their flags.

III. Ground Station Software

The ground station plays a role as a terminal for end users to monitor and command the UAV helicopter through the wireless communication channel. In the flight tests, data of the UAV helicopter are transferred from the onboard system to the ground station and displayed. The task of the ground station is to provide a friendly and realistic interface for users to monitor the process of the flight tests. Different methods of data visualization are to be implemented. In this section, we introduce the framework for developing the ground station software system. We particularly highlight

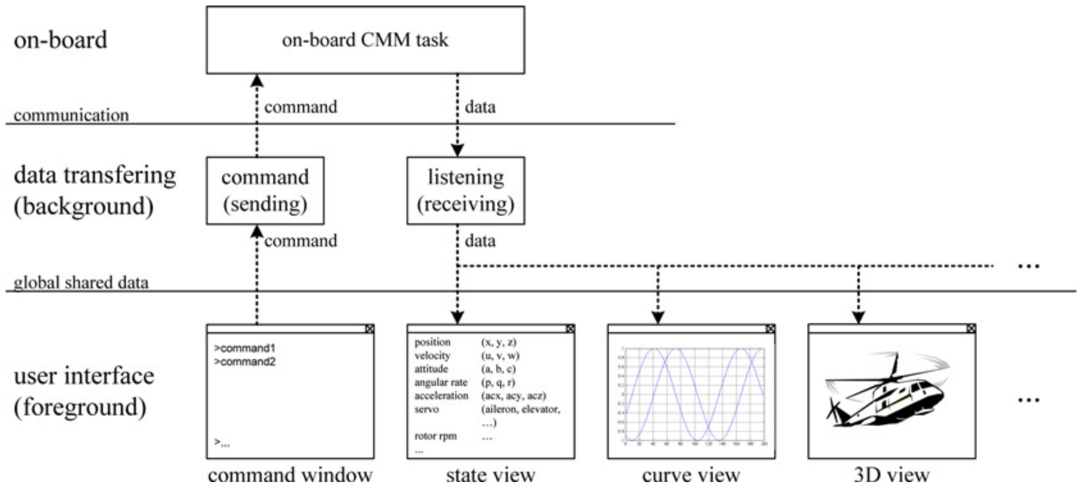


Fig. 7 Framework of the ground station software system.

the development of a 3D view interface, which is capable of transforming the data received from the helicopter into a realistic 3D view on the ground station.

The framework of the ground station software system is depicted in Fig. 7, which has two layers, i.e., the background layer and the foreground layer. Data transferring runs in background. This layer collaborates with the onboard system (i.e., the CMM task thread) through a wireless channel, receiving data from and sending commands to the onboard system. Two separate threads are created for the receiving and sending actions, respectively. In the program, the receiver thread keeps reading the serial port connected to the wireless device and adding received data to shared global storage once they are received. The sender thread keeps waiting for user's commands and writing it to the serial port once a command is captured. The read/write operation upon serial port collaborates with corresponding write/read operation on the onboard system. The shared global data are the media between the background layer and the foreground layer. The global data are dynamically updated. The foreground layer consists of a variety of views displaying the in-flight data. Four kinds of views have been developed in our system up to now, i.e., the state view, curve view, 3D view and command view. The state view shows basic states of the helicopter in a manner of a list of texts. The curve view shows in-flight data in 2D coordination graphs, in which data are generally displayed as a function of time. The 3D view is to reconstruct the actual motion of the helicopter in a more realistic 3D style.

The ground station software system is run on a laptop with the *Windows XP Professional*. Such a commercial operating system provides strong support for the development of user interfaces and many developing tools. *Visual C++ 6.0* is employed to develop the ground station software system. In this version, document-view structure based on the *MFC* (*Microsoft Foundation Class*) library is recommended by *Microsoft* for application oriented development.[24] Our framework uses a similar structure as the *MFC*. The global shared data are hosted in a document class, in which a variety of methods for data operation and visiting are integrated. This document class is the kernel of the program, which links all communication threads and functions of the multiple displaying views. The communication threads receive data from and send data to it dynamically. Displaying views, as visualization windows of document contents, periodically visit the contents of the document and update their displaying of new data received. A brief description of such a program is given in the following.

document class
init
  create communication threads
  (pass pointer to this document to threads as parameter)
  create views
  (pass pointer to this document to these views)
  create timer

```
ontimer
    loop {
    get pointer to next view
    if the pointer is null(end), exit loop
    call the updating function (onupdate) of that view
    }
onusercommand
    get the user command string inputted by user
    parse the command
    storage the translated command code and parameter
view class
onupdate
    get the pointer pointing to the document
    get new data in the document
    draw view according to the new data
communication thread 1 (receiver)
    loop {
        read serial port for communications
        if new data received {
            storage new data in the document
        }
    }
communication thread 2 (sender)
    loop {
        look up to the document if new command captured
        if there is new command {
            translate command and parameter in telegraph
            write telegraph to communication serial port
        }
    }
```

The document class has three main member functions. The *init* function is called to initialize the document and create threads, views and updating timer. When threads and views are created, a pointer of the document is passed to them to link them together. The document itself keeps an array of pointers to these views as well. The timer is finally created to send updating signals periodically. The timer message is handled by the member function *ontimer*. In every cycle when the timer message is captured, the *ontimer* function searches all views linked to the document and call their updating functions (*onupdate*) one by one. *onusercommand* is the user command handling function that is integrated in the document class. Once the user input a command through some interface items such as a menu or an edit control box, this member function is called. It first gets the string the user has inputted, then parses and translates it in an internal representation carrying command code and parameters. The translated code and parameters are then put in the document to be sent to the onboard system by the communication thread. Views are defined in the view classes with respective types. A common method is use to define all view classes. The *onupdate* member function is called every time when the data displays need to be updated, mostly when new data are added to the document. In *onupdate*, it first gets the pointer pointing to a document, and visits the content of the document. A drawing function is then called to display new data. The communication threads keep working in a receiving and sending loop, in which the receiver thread keeps reading from the communication serial port and adding data in the document once received, and the sender thread keeps looking up to the document to check if there is any new user command. Once a new command found, it translates the command into a telegraph and writes the telegraph to the communication serial port.

Figure 8 is a demonstration of the ground station user interface. The main window contains a number of child windows to display the in-flight data received from the helicopter. The left hand side of the window is the state view.

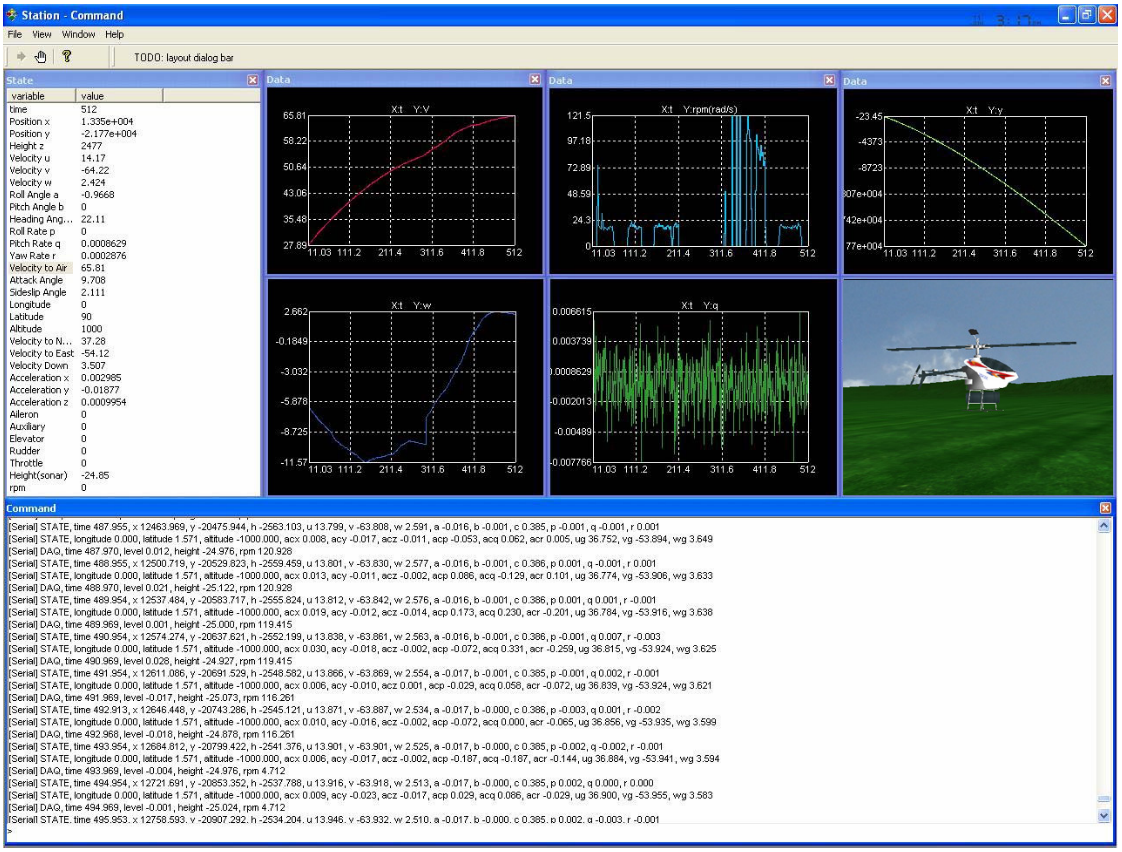


Fig. 8 User interface of the ground station software system.

It consist of two columns, the left column listing the state variables including the position, velocity, attitude, angular rate, acceleration, servo position, etc., and the second column displays the values of the corresponding variables. The bottom part is a command view. An input bar is placed at the bottom of the command view. Users can issue commands to the UAV through this panel. The upper part of the command view panel is an area listing packages received. They are pushed up to down as new packages arrive. The main part is made up of a number of curve views and a 3D view. These curve views display selected variable(s) as a function of time. The 3D view shows the 3D model of the helicopter together with the environment model to realistically simulate the actual motion of the helicopter in the sky. It also provides some additional features for users to adjust the viewing point and viewing range, allowing users to get virtual visions such as from a far distance or a position in the sky. As the 3D view is an innovative feature requires relatively advanced and complicated programming tools, we briefly highlight its design procedure in the following subsection.

A. 3D View Development

The 3D virtual view of the helicopter is very useful when the UAV helicopter flies beyond the visible range of users in the ground station. It provides users the realistic knowledge of the helicopter status. Such a requirement is common for unmanned vehicles to perform practical tasks. The development of the 3D view on our ground station is done in three stages. In the first stage, the 3D models of helicopter and ground environment are created using a toolkit called *3ds max*. In the second stage, *OpenGL* programs are developed to apply kinematical transformations upon these models. Finally, we integrate the 3D view into the overall ground station software system.

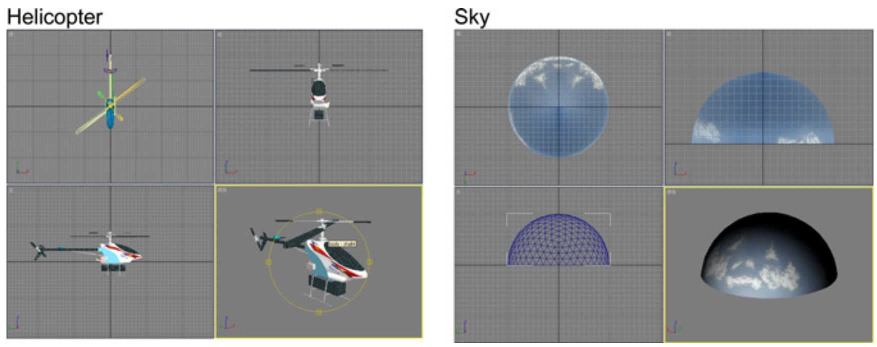


Fig. 9 Model development in *3ds max*.

1. Model Development

A 3D object is represented by a set of vertices and a series of polygons depicting its shape. Each vertex is described by a triple of float numbers representing its position. Each polygon is described by a series of vertices representing its boundary points. Although a 3D object can be constructed in a statement by statement fashion to create required vertices and faces, it will needs a large amount of codes if the model is complicated or needs fine drawing.

In our work, both the helicopter and environment are implemented by 3D models. These models are developed offline using the *3ds max* toolkit and stored to 3ds files preceding *OpenGL* drawing. In the program, vertices and polygons are loaded from these file to construct models of the helicopter and the surrounding environment. Figure 9 shows the sample models in the development workspace. The left-hand part of the figure is the 3D model of the helicopter, which is much like the real helicopter used for in HeLion. The right-hand part is a hemisphere model to imitate the sky part of the surrounding environment.

2. 3D Drawing

OpenGL (*Open Graphical Library*) is used to create 3D models. It provides a rich collection of functions for drawing object based on vertices and polygons. As mentioned earlier, objects are represented by a set of vertices and polygons. The drawing of an object is accomplished by going through all its vertices and polygons. The framework of 3D drawing is depicted in Fig. 10, which illustrates how the 3D models created offline, data of the helicopter state and view operations from users are integrated. Both the helicopter and the environment models are loaded

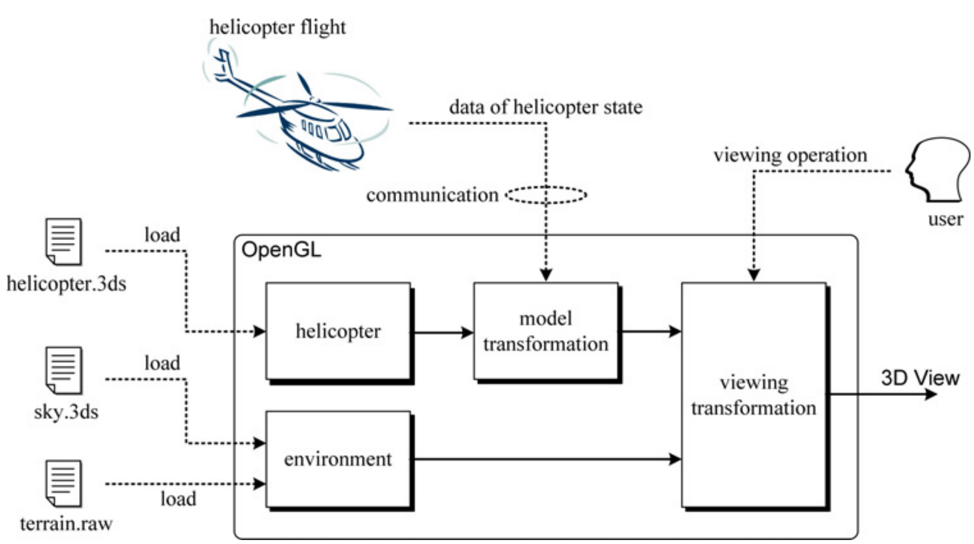


Fig. 10 OpenGL drawing.

from pre-created files. Real-time data required for the helicopter includes positions and attitudes transferred from the onboard system. View operation from users includes moving, rotating, and zooming of the virtual 3D view.

3. 3D View

The 3D view is lastly encapsulated in a class in C++ program. It is attached with global data, in which the in-flight data of the UAV helicopter are stored. To dynamically simulate the motion of the helicopter, the view is updated with a rate of 10 Hz. In every cycle, newest values of the helicopter state are read from the global data pool and the content of the 3D view is repainted accordingly. The periodical update is scheduled in the program by a timer, which is created in the initialization stage of the 3D view. In the end of each cycle, a timer message will be sent to the view to request an update, which proceeds as in the following code.

```
CTDView::OnUpdate()
{
    double pos[3] = { _data[1], _data[2], _data[3] }; //position
    double att[3] = { _data[7], _data[8], _data[9] }; //attitude
    angle += rate*period/1000; //incremental rotor angle
    SetPositionAttitudeRotor(pos, att, angle); //calculate transformation
    GLDraw(); //redraw
}
```

The *OnUpdate* function is a member of the 3D view class *CTDView*, which is called whenever a timer message is captured. The front two lines get the position and attitude from the global data pool, which is updated from time to time as the flight test progresses. The angle of the rotor is added by an incremental value every period to give an effect of rotating. Then the member function *SetPosiitonAttitudeRotor* is called to assign these states to the 3D view. This function is to calculate transformation matrices and apply them to the 3d objects as described in the previous subsection. The *GLDraw* member function is finally called to redraw the content of the 3D view.

Finally, the appearance of 3D view is illustrated in Fig. 11. Pictures are captured when the ground station software system is running. Some virtual views obtained from different viewing points are listed in left and right columns in the figure.

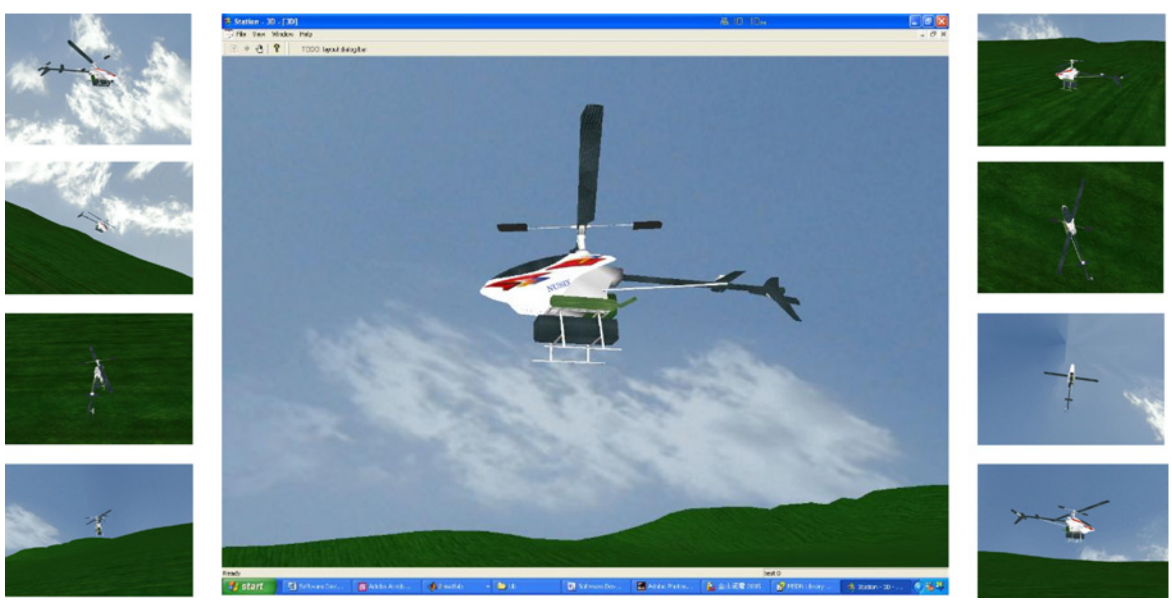


Fig. 11 The 3D view of the UAV helicopter.

IV. Software Evaluation and Test Results

In this section, we present the evaluation and actual test results of the overall software system developed together with some test flight results of the actual UAV helicopter.

A. Evaluation of Working Load of the Software System

We have performed a thorough test on the developed software system. Working load of the onboard system is evaluated by running multiple tasks on the onboard computer. To evaluate the working load of task threads, we record the time used by task threads in every cycle in log file. Figure 12 shows a graph of time consumption profiles by task threads with data being recorded from an actual test flight. We note that the communication task is scheduled to transfer data once per second due to the bandwidth limitation of the wireless communications. The data logging thread is also operated at a slower pace as it generally requires a large amount of the CPU consumption time.

The time consumptions of all task threads are summed up in Fig. 13 as the time consumption of the main thread. The usage rate of the onboard CPU can be calculated as the ratio of the total time consumption and the length of period, which is 20 ms used in the actual test. From the result shown in Fig. 13, we can determine that the lowest usage rate of the CPU is about

$$\text{usage}_{\min} = \tau_{\min}/T = 0.38/20 = 1.9\%$$

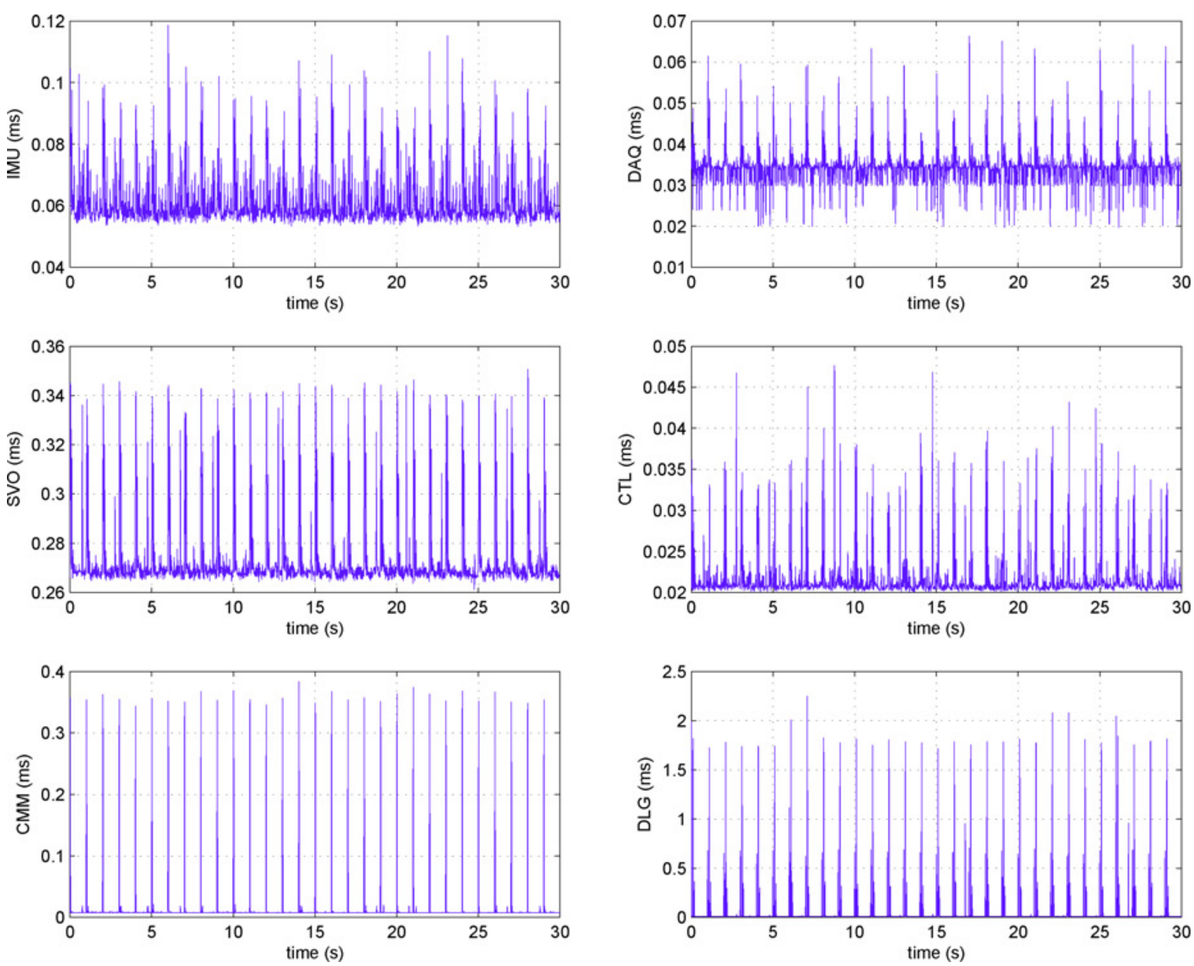


Fig. 12 Time consumption by task threads.

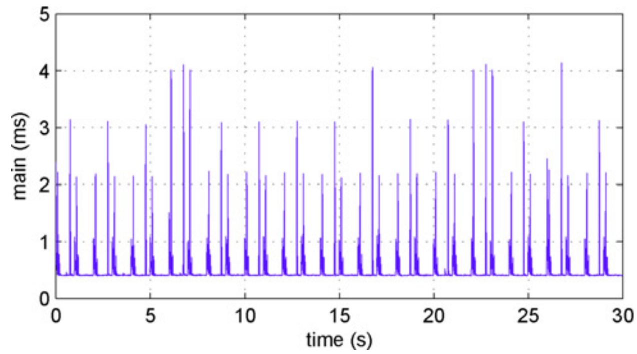


Fig. 13 Total time consumption of the main thread.

and the highest peak is

$$\text{usage}_{\text{max}} = \tau_{\text{max}}/T = 4.5/20 = 22.5\%$$

where τ_{min} and τ_{max} stand respectively for the minimum and maximum total time consumptions by all threads in one cycle, and T is the period of the cycle. The peak of the CPU usage rate comes with the large working load of data logging and communications, which occurs once every 50 cycles, i.e., 1 second. The average time consumption in each cycle is about 0.52 ms. Thus, the average CPU usage rate is

$$\text{usage}_{\text{average}} = \tau_{\text{average}}/T = 0.52/20 = 2.6\%$$

The low usage rate of the onboard CPU is ideal for guaranteeing the reliability of the overall software system. To balance working load, the communication and data logging threads have to be scheduled in a more distributive and efficient way. Some optimization technique might be utilized to yield a more efficient and optimal management of the system.

B. Reliability Improvement

It is evident from the dynamic model of the UAV helicopter constructed through in-flight data collected from actual flight tests. The UAV helicopter is an open-loop unstable system. Additional features and measures need be taken to improve the reliability of the software system and to ensure the safety of helicopter in the situation when the automatic control system implemented is malfunctioned. In this subsection, we present some solutions for such a situation.

1. Onboard Simulation

Although the control laws have to be verified by intensive simulation in MATLAB and SIMULINK offline on the ground station or a desktop, there are still possibilities to error in the process of software implementation. Besides, faults in other parts of the onboard software system may cause serious problems in actual control of the helicopter as well. Thus, the onboard simulation is necessary for checking the validity of the software code of the control laws implemented. Any faults in software or in control system detected by the onboard simulation will greatly minimize potential risks and accidences, which might happen in actual flight tests.

In our work, a software block is developed and integrated in the onboard software system to simulate the performance of the UAV helicopter system. It uses the dynamic model of the aircraft obtained through the modeling and identification process based on in-flight data collected from actual test flights. The function of this simulation block acts like a virtual helicopter replacing the real UAV. Although it is also an offline simulation, its results are, however, directly sent to the ground station for verifying both the accuracy of the control system implementation and communication channels. Such an approach is proven to be very effective in detecting coding errors and faults in the implementation of control algorithms.

2. Emergency Handling and Black Box Data Saving

This additional safety measure is a result that we learned from a serious crash of our UAV helicopter. There are many sources that would cause failures in the UAV control system, which includes drastic changes in environment, hardware failure, GPS disorder and problems in control system design and software implementation. A mechanism for handling emergency situations is built in the onboard software system. At every cycle, before applying control action, the control task thread checks all data received from the IMU and other devices. Once any abnormality is observed, the emergency control function is called up immediately to alert the technical people on the ground, which might give enough time for the ground pilot to switch the UAV system from the automatic control mode to that under manual control.

It is also very important to keep logged data as much as possible on emergency situations as they can be used to identify problems that cause the incidents. However, in an exceptional occasion when a crash occurs, all tasks run onboard including data logging are terminated unexpectedly. In a normal operation, the data logging file is opened at the beginning of a flight test, and is amended with in-flight data during the test, and finally closed and saved at the end of the test. In an abnormal situation, the data logging file is likely to be corrupted, resulted in losing all data. If the process is interrupted, the whole file will be damaged. A mechanism similar to the black box in commercial aircraft is implemented to keep saving logged data even in a crash. Such a feature is illustrated in the program below:

Initialization stage
do nothing
logging stage
1st time (the first 50 cycles)
open logging file in writing and appending mode
write 1st pack of data to logging file
close logging file
2nd time (the next 50 cycles)
open logging file in writing and appending mode
write 2nd pack of data to logging file
close logging file
. . .
n-th time
open logging file in writing and appending mode
write n-th pack of data to logging file
close logging file
. . .
finalization stage
do nothing

As illustrated in the program above, the new feature enables the data logging process to complete data writing and saving in every 50 cycles, i.e., about 1 second. If an accident occurs, all data saved before it will remain safe and can be used for analyzing the accident.

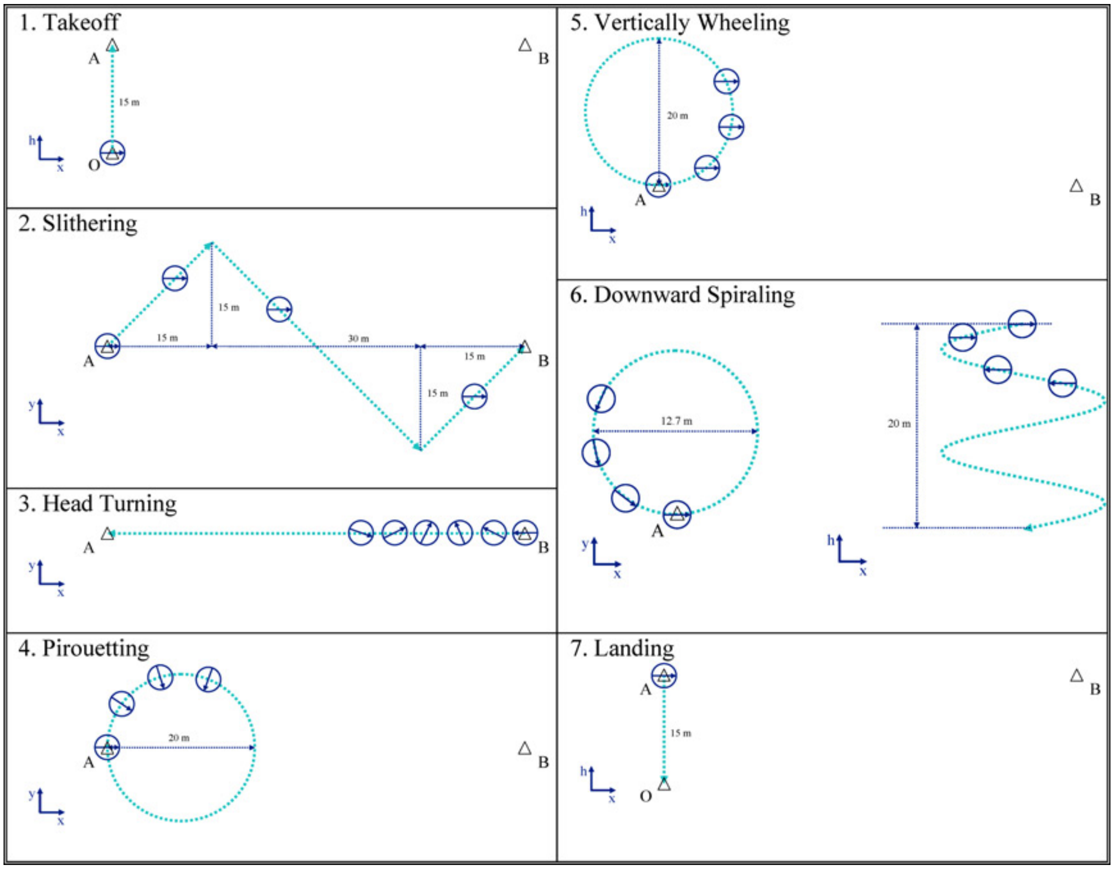
C. Actual Flight Test

We have performed flight tests such as hovering, forward flight, trajectory tracking and scheduled flight. We present in this subsection the test result of a scheduled flight.

The schedule for demonstration is designed as in Table 4, in which the ‘x-h’ and ‘x-y’ represent the vertical plane and horizontal plane, respectively. More specifically, the UAV helicopter is commanded to automatically take off, and then perform a series of flight actions, such as slithering, head turning, pirouetting, vertically wheeling, and downward spiraling, and finally automatically landing to the initial position where the helicopter lifts off.

1. Takeoff. The UAV helicopter launches its engine and lifts form a ground position (marked as ‘O’) to Position A, 15 m above the ground.
2. Slithering. The UAV moves in both forward and sideward direction, and follows a zigzag path, from Position A to Position B. The distance between A and B is 60 m.

Table 4 Flight Schedule of the Actual Test Flight.



3. Head Turning. The helicopter is commanded to fly in a straight path from B to A, with its head continuously rotating in the yaw direction.
4. Pirouetting. The helicopter flies along a circle of 20 m in diameter with its head steadily pointing to the center of the circle.
5. Vertically Wheeling. In this action, the UAV is commanded to follow a circle of 20 m in diameter in the vertical plane. The diameter of the circle is 20 meters.
6. Downward Spiraling. The helicopter flies in the backward direction along a downward spiral path.
7. Landing. The UAV helicopter descends to the starting point, i.e., Position O, on the ground.

The behavior-based plan for this flight schedule is shown in Fig. 14, in which each node represents a running state of the helicopter, corresponding to a specific flight action, and each arrow line represents an event that triggers the next flight behavior. In the plan, the flight actions of the UAV are clustered one after another by events, and finally it returns to the ready state.

The results of the actual test flight are given in Fig. 15, in which the position and the heading angle of the helicopter are captured. Variables x and y are, respectively, the displacements in the north and east directions, h is the height with respect to the ground, and ψ is the heading angle respective to the north. In the figure, the dotted lines represent the desired trajectories and the solid lines are actual flight results. We note that the GPS position signals we have received have an accuracy of ± 3 m. The results show that the software system and the automatic control are quite effective and reliable. Interested readers might wish to view or download a video clip captured during the actual test flight via this link: http://hdd.ece.nus.edu.sg/∼uav/wmv/session3.wmv.

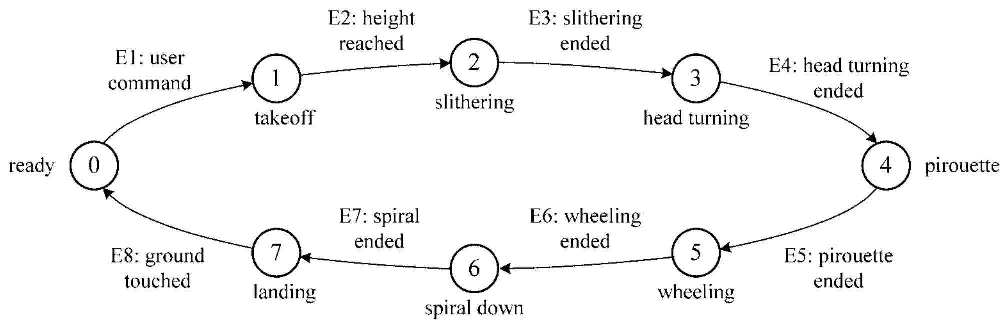


Fig. 14 Flight Plan of the Actual Test Flight.

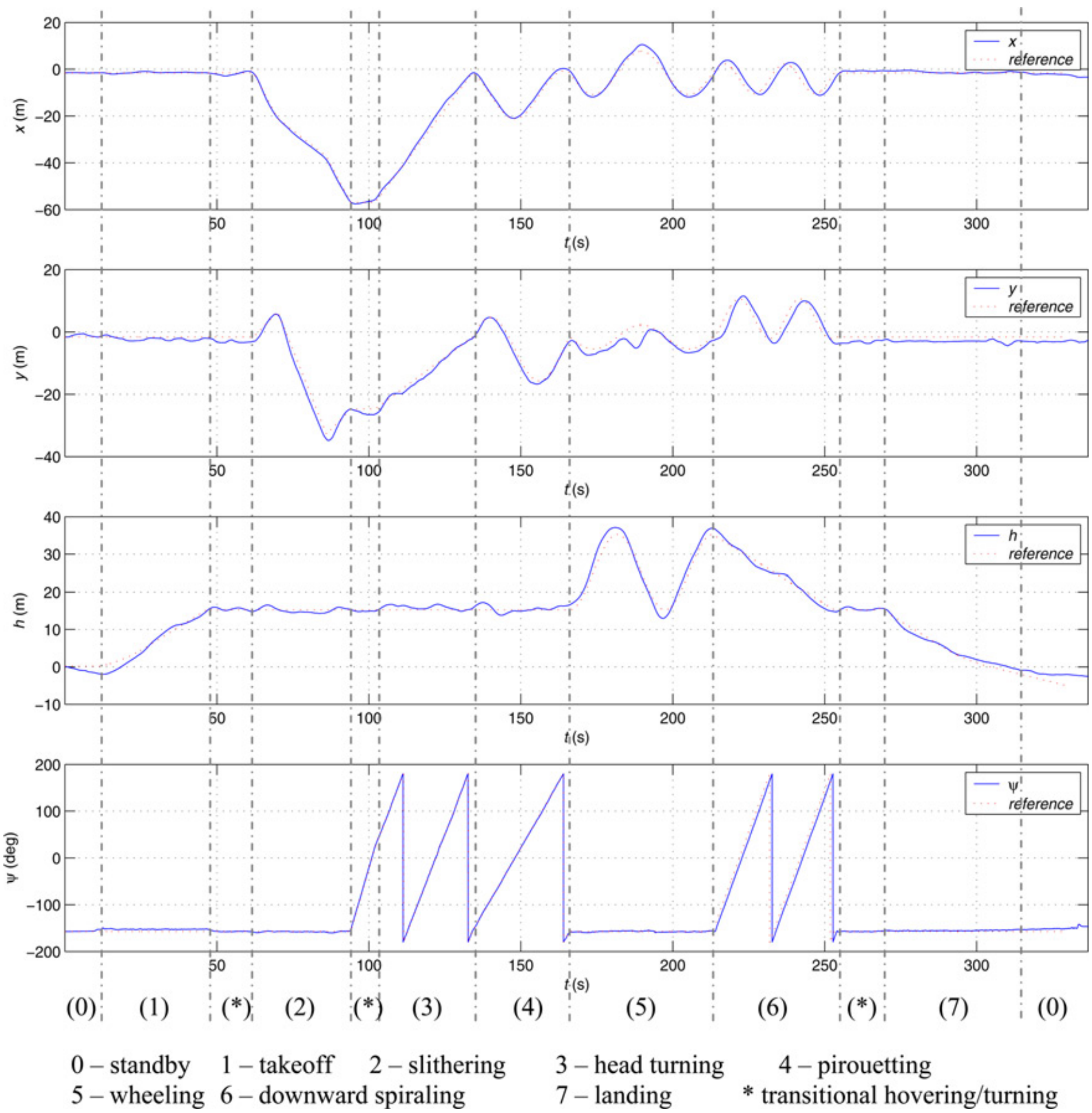


Fig. 15 Result of the Actual Test Flight.

V. Conclusion

A software system for an unmanned helicopter is presented in this paper. Both the onboard and ground station systems are developed. The onboard software system has used a framework of multiple task threads to perform tasks including inertial measurement, data acquisition, automatic control, servo driving, communications and data logging. Software methods of synchronization are employed to manage these tasks. A scheme of time allocation is designed for both software and hardware together with a behavior-based architecture for implementing automatic control algorithms. The ground station software has used a framework with two layers, i.e., data transferring in background and information visualization in foreground. A unique feature of a 3D monitoring system has also been developed on the ground station for a more realistic reconstruction of the helicopter movement in the sky. The software system has been thoroughly tested through actual flight tests of the UAV helicopter.

The paper actually covers a range of common subjects for all unmanned vehicles such as hardware driving, task threads scheduling and control implementation. The software solution presented in this work can also be used to other unmanned vehicles with minimal modifications. Indeed, the development of a universal software framework for all unmanned vehicles is our primarily focus in the near future.

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