Design and Development of Autonomous Uninhabited Air Vehicles at ITB: Challenges and Progress Status

A. Budiyono[‡]

Abstract— **An uninhabited air vehicle has found diverse applications for both civil and military missions. To achieve the stated mission, the vehicle needs to have a certain level of autonomy to maintain its stability following a desired path under embedded guidance, navigation and control algorithm. To meet the increasingly more stringent operation requirements, the UAVs rely less and less on the skill of the ground pilot and progressively more on the autonomous capabilities dictated by a reliable onboard computer system. A model helicopter was proposed and used as a flying test-bed for the purpose of developing the autonomous capability. The ability of the helicopter to operate in the hovering mode makes it an ideal platform for a step-by-step autonomous capability development. On the other hand, a small helicopter exhibits not only increased sensitivity to control inputs and disturbances, but also a much richer dynamics compared to conventional UAVs including: higher bandwidth, hybrid modes, non-holonomic, under-actuation, multi-input-multi-output, and non-minimum phase. These factors make model helicopters, as a flying robot, more difficult to control. The paper addresses the challenge of building an autonomous aerial system using a mini scale rotorcraft. The enabling technology building blocks were identified and a development scheme was proposed based on available resources. Recent progresses were reported in the modeling, design and development of embedded robust control system for autonomous helicopter.**

Keywords— **autonomous system, onboard system algorithm, rotor unmanned aerial vehicle, MIMO aerospace system**

NOMENCLATURE

u, v, w	velocity components in x, y and z-body axes system, fps
u_0, v_0, w_0	values of u, v, w at trim condition, fps
p, q, r	roll, pitch and yaw rates, rad/s
ϕ, θ, ψ	roll, pitch and yaw angles, rad
δ_{lat}	lateral deflection of main rotor, rad
δ_{lon}	longitudinal deflection of main rotor, rad
δ_{ped}	pitch deflection of tail rotor blade, rad
δ_{col}	pitch deflection of main rotor blade, rad
a, b	main rotor longitudinal and lateral flapping motions, rad
c, d	stabilizer bar longitudinal and lateral flapping motions, rad
τ_s, τ_f	stabilizer and main rotor time constants
A_{lon}, B_{lon}	longitudinal input derivatives
A_{lat}, B_{lat}	lateral input derivatives

I. INTRODUCTION

AN Unmanned Aerial Vehicle can be defined as an aerial vehicle that uses aerodynamic and propulsion forces to sustain its flight along a prescribed path without an on-board pilot. The UAV technology has the potential applications in many areas such as environmental monitoring and protection, meteorological surveillance and weather research, agriculture, mineral exploration and exploitation, aerial target system, airborne surveillance for military land operations, and reconnaissance missions. The unmanned small scale helicopters are particularly suitable for demanding problems such as traffic or volcanic areas surveillance, detailed area mapping, video footage recordings and crop dusting or spraying.

A recent progress in the supporting technologies has enabled the development of semi to fully autonomous UAV. This includes the availability of compact, lightweight, affordable motion detecting sensors essential to the flight control system and compact lightweight low-cost computing power for autonomous flight control. The common availability of Global Positioning Satellite Navigation Systems has also a direct positive impact to the navigation system development for UAVs. The discontinuation of selective availability of the system has further fueled increased interest in using GPS not only for navigation but also for closing the control loop. Particularly, the integration of satellite navigation and inertial sensor data with flight control systems enable wider application of the UAVs. In general, the availability of global UAV knowledge-base has helped advance the frontier of this developing technology.

To successfully design an autonomous UAV, core and enabling technologies have to be identified. It is well known that the core technologies for UAVs comprise airframes, propulsion systems, payloads, safety or protection systems, launch and recovery, data processor, ground control station, navigation and guidance, and autonomous flight controllers. In the ongoing research project, most of the enabling technologies are given and the effort will be centered at developing an autonomous navigation, guidance and control system for the UAV.

The present work deals with the conception, design and development of autonomous system for a small scale unmanned helicopter. The model helicopter was chosen as the flying test-bed due to its ability in demonstrating numerous issues in the study of complex dynamical systems. As a research vehicle, a small scale helicopter poses dif-

---

[‡] Department of Aeronautics and Astronautics, Bandung Institute of Technology, Jl. Ganesha 10, Bandung 40132, Indonesia agus.budiyono@ae.itb.ac.id

ferent research challenges including the fully autonomous flight, collision and obstacle avoidance, hybrid control system, filtering design, dynamic trajectory planning, sensor fusion and coordination flight. The paper identifies critical aspects of the project and reports progresses towards designing a fully autonomous model helicopter for a variety of mission applications.

II. PRIOR ART AND LITERATURE SURVEY

The viability of the small scale helicopter as a multipurpose research vehicle has driven great interest in recent past. The MIT UAV team successfully developed an autonomous aerobatic helicopter [1] - [9]. The development relied on the modeling framework of the miniature helicopter dynamics. A methodology for designing model-based control strategies for autonomous aerobatic maneuver was proposed and validated experimentally. Referring to previous work by Mettler [10] at Carnegie Mellon Robotics Institute, the basis for a simplified modeling framework was considered to stem from the fact that the dynamics of small-scale helicopters is dominated by the rotor response [11]. The major contribution of the modeling approach was the achievement of accurate model suitable for high bandwidth control without the need of expensive and time-consuming system identification or wind-tunnel testing. The developed controllers were divided into two modes accompanied by a smooth transfer logic for switching between the modes. The task of the first controller was to guide the helicopter along equilibrium or trim trajectories. A linear quadratic regulator (LQR) technique was implemented to a reduced order helicopter model appended with integrators on the control variable tracking errors. To accommodate rapid changes in gain values –associated with the maneuvers– with the scheduled forward speed, a novel gain-scheduling scheme based on discrete switching of gain tables with bumpless transfer logic was used. The experimental validation also demonstrated that the closed loop dynamics under trim trajectory controllers can be approximated by a set of decoupled first-order models useful for time-efficient motion planning algorithms. The second type of controllers were designed based on the study on skilled pilot strategies particularly for the execution of aerobatic maneuvers. Piece-wise linear angular rate command profiles were developed based on the pilot commands during the maneuvers. Using a library of these maneuvers, the work also proposed a hybrid model of the helicopter dynamics under feedback control which is suitable for use in guidance or motion-planning algorithms. The maneuver was defined as a sequence of three phases: leveling, rate-trajectory following (primary maneuver) and settling in the trim-trajectory mode. The developed hybrid model represents each maneuver as a discrete change in the states (forward velocity, turn rate, altitude rate, triad positions and heading). As demonstrated by experimental data, the hybrid model provided a simplified yet realistic description of highly-maneuverable small-scale helicopter dynamics under the feedback control system. In the autonomous control system design, an *Extended Kalman Filter* (EKF) was implemented to blend information from different sensors for an efficient state estimation algorithm [11]. The new representation of attitude error as suggested by Frazzoli was used in the EKF implemented for the helicopter state estimation algorithm. The real-time control system was developed using a Hardware-In-the-Loop (HIL) simulation system which allows high fidelity representation of the real signal's time-dependence.

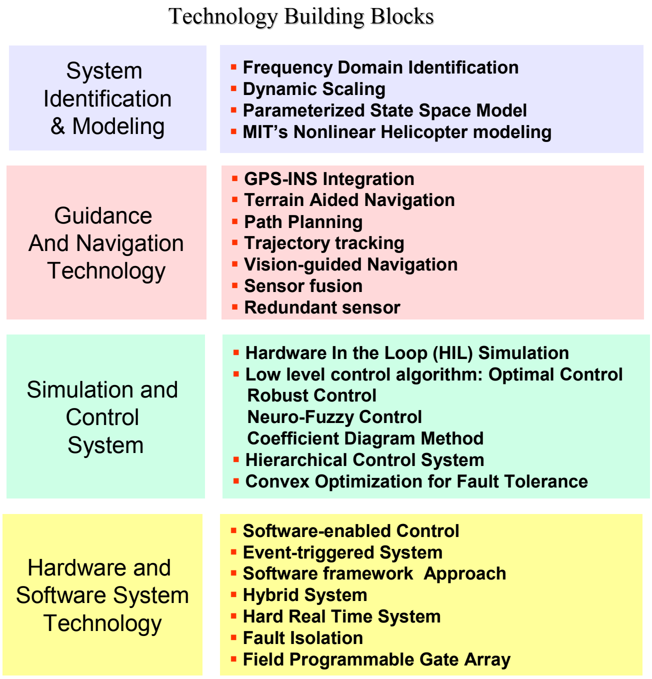
At Georgia Tech, the *Open Control Platform* (OCP)– a new object-oriented real time operating software architecture– has been used onboard the GTMAX UAV helicopter to compensate for the simulated in-flight failure of a low level flight control system. The compensation was performed by reconfiguring the software-enabled control (SEC) systems autonomously[12]. The SEC program was executed to create enabling technologies to make the UAV more reliable, robust and agile. An extensive simulation, including *Software-In-the-Loop*(SIL) and *Hardware-In-the-Loop* (HIL), has been conducted as part of the autonomous system design and development[13]-[22]. The use of simulation and sensor data playback has enabled the substantial reduction on flight test time to develop the navigation system[15],[16],[19].The work proposed sensor fusion technology[15] and minimum complexity guidance and flight control system implemented in the experimental UAVs[23]. In the proposed sensor fusion scheme, various data from flight sensors is fused into one navigation solution in the state estimator. An EKF approach was used to integrate data from navigation sensor equipment. Propagated IMU-data was fused with discrete updates from two altimeters (with different range) and DGPS. In the field of avionics architecture, one remarkable research direction was the use of a single GPS for the navigation and flight control system of a stable fixed-wing UAV. The work in this area was primarily inspired by previous research at MIT[24]. The viability of designing inexpensive architecture, along with a relatively simple processor, will pave the way for the extremely low-cost flight control and guidance systems. Another novel contribution was the use of Pseudo Control Hedging (PCH) in the adaptive flight control scheme for improving tracking performance of an autonomous helicopter. Using this architecture, a consolidated reference command that includes position, velocity, attitude and angular rate may be provided to the control system. The use of PCH along with expressions for the poles of the combined inner-outer loop error dynamics alleviate bandwidth separation requirements[13].

The autonomous helicopter research at Carnegie Mellon Robotics Institute was centered on the development of vision-guided helicopter for a number of goal applications[25],[26]. The demonstrated capabilities includes vision-based stability and control, autonomous take-off and landing, trajectory following, aerial mapping and object recognition and manipulation. The proposed scheme combined vision with other low-level sensors such as accelerometers and range sensors to produce robust autonomous navigation systems. An array of on-board sensors were integrated with vision to form a robust state estimator.

The state estimator ultimately fused data from the visual odometer, an inertial measurement unit (IMU), a GPS receiver, a flux-gate compass, and a laser range finder[25]. Ref.[27] describes the integration of a 3-D scanning laser rangefinder with the autonomous helicopter for terrain modeling and structure inspection. One aspect of helicopter research at Carnegie Mellon was the system identification modeling of a miniature helicopter as elaborated in Ref.[10]-[29]. In those work, a complete dynamic model was derived for both hover and cruise flight conditions. In addition to standard helicopter flight characteristics, the model explicitly takes into account the influence of the stabilizer bar dynamics. The accuracy of the developed model was validated by the comparison between predicted and actual responses from the model and the flight experiments, and between key identified parameters and their theoretical values.

BErkeley AeRobot (BEAR) team has developed an autonomous helicopter and planning and control system based on hybrid system theory[30]- [45]. Ref.[46] dealt with the hybrid modeling of an unmanned helicopter. The hierarchical modeling and simulation framework utilized a system-level design tool called *Ptolemy II* that supports integration of multiple models of computation. The hierarchical hybrid modeling was realized by combining continuous-time models with finite state automata. Issues such as breakpoint handling, event detection and invariant techniques were investigated. In another study, output tracking for a mini helicopter was proposed in Ref. [32]. It was shown that exact input-output failed to linearize the whole state space and amounted to unstable zero dynamics. When the couplings between moments and forces were neglected, it was demonstrated that the approximated system was full state linearizable by choosing positions and heading as outputs. Further, the approximation of the system was differentially flat, thus state trajectory and nominal inputs can be generated from a given output trajectory [32]. The use of differential flatness approach was based on the previous work at Caltech as elaborated in Ref.[47]-[51]. Ref. [38] and [35] further investigated the application of differential flatness for full authority helicopter control system. The property of differential flatness is very important for a real-time trajectory generation. A more comprehensive study was done to compare three different control methodologies for helicopter autopilot design: linear robust multi-variable control, fuzzy logic control with evolutionary tuning and nonlinear tracking control as given in Ref.[45]. The robust and fuzzy controller was shown to be capable of handling uncertainties and disturbances in the operating regime limited to near hover condition. To cover a wider region in the flight envelope however, a nonlinear control system design was required. However, in this case, an accurate modeling of the whole system would be necessary. The approach taken to address the insufficiency of the pure feedback linearization was to use the robust controller based on perturbed linearized system. The *Flight Vehicle Management System* (FVMS) , acting as the high-level controller in the hierarchical control scheme, was then designed to select the proper type of controller depending on the flight conditions and commanded behavior. Ref. [40] further proposed a formal approach to reactive system design, implementation and validation implemented on the FVMS of unmanned helicopter. A design tool called POLIS was used to automate the design problem and the validation techniques allowing the reduction of the prototyping time. Simulation of the entire design was performed within *Ptolemy II* environment. More recent results were reported in Ref.[33]. The proposed system executed high-level mission objectives by progressively substantiating them into machine-level commands. The scheme allowed the propagation of information from various sensors to the higher level layers for reactive decision making. The proposed system has been successfully implemented on a number of model helicopters. A scalable multi-agent coordination was enabled by connecting each small helicopter with standardized wireless communication protocol. The results from way point navigation, pursuit-evasion, tracking of a moving targets and autonomous landing showed the viability of the design of highly maneuverable intelligent flying robots.

In addition to the work done by the above research groups, the uses of model helicopters for research were reported in Europe as in [52]- [53]. The helicopter team at ETH Zurich has developed autonomous capabilities using comparable approaches as those of the corresponding groups in the United States. One primary feature in the approach was the extensive development and application of Hardware-In-the-Loop for testing and validating real-time control systems[53].



Technology Building Blocks

System Identification & Modeling	▪ Frequency Domain Identification ▪ Dynamic Scaling ▪ Parameterized State Space Model ▪ MIT's Nonlinear Helicopter modeling
Guidance And Navigation Technology	▪ GPS-INS Integration ▪ Terrain Aided Navigation ▪ Path Planning ▪ Trajectory tracking ▪ Vision-guided Navigation ▪ Sensor fusion ▪ Redundant sensor
Simulation and Control System	▪ Hardware In the Loop (HIL) Simulation ▪ Low level control algorithm: Optimal Control Robust Control Neuro-Fuzzy Control Coefficient Diagram Method ▪ Hierarchical Control System ▪ Convex Optimization for Fault Tolerance
Hardware and Software System Technology	▪ Software-enabled Control ▪ Event-triggered System ▪ Software framework Approach ▪ Hybrid System ▪ Hard Real Time System ▪ Fault Isolation ▪ Field Programmable Gate Array

Fig. 1. Technology building blocks of autonomous system development

III. PROBLEM DESCRIPTION: UAV SYSTEM DEVELOPMENT

The present work deals with the development of autonomous system for a small scale X-Cell-60 helicopter called MINERVA (MINiature hElicopter for Research on Vehicle's Autonomous system) project. The technology building blocks are identified early in the development process as shown in Fig.1. The approach taken in the step-by-step development procedure is model-based therefore substantial effort has been centered on the development, simulation and validation of helicopter dynamics model. The accuracy of the developed model in this case will determine the performance of the overall autonomous control system. The avionics system is developed to realize the requirements of autonomous control and navigation design for the helicopter. The low-level controllers are designed concurrently while the helicopter model is constructed and successively refined. In the preliminary step, the control methodology is designed based on the available model in the relevant literatures. As the baseline, the model for R-50 helicopter developed at Carnegie Mellon and one for X-Cell 60 developed at MIT are studied and used for simulation. For clarity, only the first model will be presented in this paper.

A. Helicopter dynamics modeling

The basic linearized equations of motion for a model helicopter dynamics are derived from the Newton-Euler equations for a rigid body that has six degrees of freedom to move in space. The external forces, consisting aerodynamic and gravitational forces, are represented in a stability derivative form. For simplicity, the control forces produced by the main and tail rotor are expressed by the multiplication of a control derivative and the associated control input. Following [10], the equations of motion of the model helicopter are derived and categorized into the following groups.

Lateral and longitudinal fuselage dynamics. Using the Newton-Euler equations, the translational and angular fuselage motions of the helicopter can be derived as the following set equations:

$$\begin{aligned}
\dot{u} &= (-w_0 q + v_0 r) - g\theta + X_u u + +X_a a && (1)\\
\dot{v} &= (-u_0 r + w_0 p) - g\phi + Y_v v + +Y_b b && (2)\\
\dot{p} &= L_u u + L_v v + ... + L_b b && (3)\\
\dot{q} &= M_u u + M_v v + ... + M_a a && (4)
\end{aligned}$$

The stability derivatives are used to express the external aerodynamic and gravitational forces and moments. X_a, Y_b denotes rotor derivatives and L_b, M_a the flapping spring-derivatives. They are all used to describe the rotor forces and moments respectively. General aerodynamic effects are expressed by speed derivatives given as $X_u, Y_v, L_u, L_v, M_u, M_v$.

Heaving(vertical) dynamics. The Newton-Euler rigid body equations for the heaving dynamics is represented by

$$\dot{w}= (-v_0 p + u_0 q) + Z_w w + Z_{col}\delta_{col} \qquad (5)$$

The centrifugal forces represented by the terms in parentheses are relevant only in cruise flight.

Yaw dynamics. The augmented yaw dynamics is approximated as a first-order bare airframe dynamics with a yaw rate feedback represented by a simple first-order low-pass filter. The corresponding differential equations used in the state-space model are also given in appropriate stability derivatives as follows

$$\begin{aligned}
r &= N_r r + N_{ped}(\delta_{ped} - r_{fb}) && (6)\\
\dot{r}_{fb} &= K_r r - K_{rfb} r_{fb} && (7)
\end{aligned}$$

Coupled Rotor-stabilizer bar dynamics. The simplified rotor dynamics is represented by two first-order differential equations for the lateral(b) and longitudinal(a) flapping motion. In the state-space model, the rotor model are given as:

$$\begin{aligned}
\tau_f\ \dot{b} &= -b - \tau_f p + B_a a + B_{lat}\delta_{lat} + B_d d + B_{lon}\delta_{lon} && (8)\\
\tau_f\ \dot{a} &= -a - \tau_f q + A_b b + A_{lat}\delta_{lat} + A_c c + A_{lon}\delta_{lon} && (9)
\end{aligned}$$

where the following derivatives related to the gearing of the Bell-mixer are introduced:

$$\begin{aligned}
K_d &= \frac{B_d}{B_{lat}} && (10)\\
K_c &= \frac{A_c}{A_{lat}} && (11)
\end{aligned}$$

The stabilizer bar receives cyclic inputs from the swashplate in a similar way as do the main blades. The equations for the lateral(d) and longitudinal(c) flapping motions are:

$$\begin{aligned}
\dot{d} &= \frac{1}{\tau_s}(-d - \tau_s p + D_{lat}\delta_{lat}) && (12)\\
\dot{c} &= \frac{1}{\tau_s}(-c - \tau_s q + C_{lon}\delta_{lon}) && (13)
\end{aligned}$$

The state-space model of the R-50 dynamics. The state-space model of the helicopter can be assembled from the above set of differential equations in a matrix form:

$$\dot{\underline{x}}= A\underline{x} + B\underline{u} \qquad (14)$$

where $\underline{x}= \{u, v, p, q, \phi, \theta, a, b, w, r, r_{fb}, c, d\}^T$ is the state vector and $\underline{u} = \{\delta_{lat}, \delta_{lon}, \delta_{ped}, \delta_{col}\}^T$ the input vector. The dynamic matrix A contains the stability derivatives and the control matrix B contains the input derivatives. The state-space model is readily usable for a linear control system design and synthesis.

B. Avionics system

The avionics system is designed to allow logical information flow within the UAV system in accordance with control and navigation requirements. Various information is picked-up by the sensors to measure the vehicle attitude, positions and atmospheric data. The vehicle attitude dynamics is measured using Inertial Measurement Unit (IMU) which typically consists of triad accelerometer to sense the accelerations and triad gyros to sense the Euler angles. The vehicle positions can be deducted from the accelerations or obtained from GPS measurements. The information from Inertial Navigation System (INS) and GPS can be fused to provide more reliable measurement system. Sonar altimeter can be used to give more accurate altitude information at low altitude or in the proximity to the ground. The proposed avionics system designed is given in Fig.2

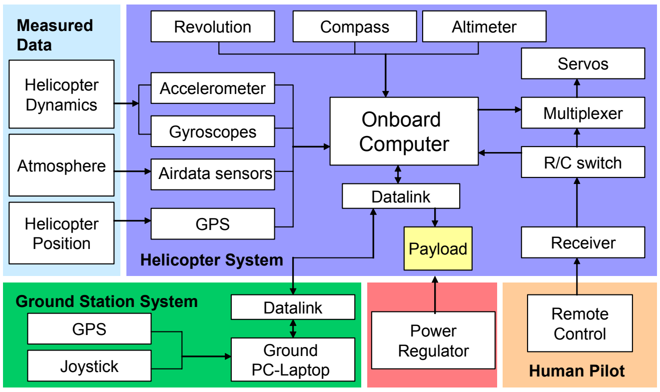


Fig. 2. Avionics system of ITB helicopter

C. Control system design

The complex dynamics of the helicopter poses different problems to control system design. A model helicopter is especially more difficult to control due to the higher bandwidth dynamics. In addition, helicopter dynamics is generally coupled, nonlinear and time-varying which suggests more intricate treatment than do the fixed-wing UAVs. The control system for helicopters is of multi-input multi-output type and further becomes complicated due to the underactuation problem. The dynamics of a helicopter is also inherently hybrid and thus calls for a hybrid hierarchical control approach. In the first phase of control system development for ITB model helicopter, two control methodologies are designed and studied. The first controller is an output tracking control designed based on the linear quadratic regulator approach [54]. The second controller is a robust linear control design using a novel coefficient diagram method (CDM) [55].

Linear Quadratic Regulator (LQR). A Linear Regulator problem in the optimal control theory represents a class of problem where the plant dynamics is linear and the quadratic form of performance criteria is used. The linear dynamics (which can be time-varying) are:

$$\dot{\underline{x}}\,(t) = A(t)\underline{x}(t) + B(t)\underline{u}(t) \tag{15}$$

and the cost is quadratic:

$$J \;=\; \frac{1}{2}\underline{x}(t_f)^T H \underline{x}(t_f) + \tag{16}$$

$$\frac{1}{2}\int_{t_0}^{t_f} [\underline{x}(t)^T Q(t)\underline{x}(t) + \underline{u}(t)^T R(t)\underline{u}(t)]dt$$

The optimal feedback control law can be derived by identifying the *Hamiltonian* of the system and using the *Hamilton-Jacoby-Bellman* equation to ensure the optimality. To use the LQR design for path tracking control, the regulator problem must be recast as a tracking problem. In a tracking problem, the output y is compared to a reference signal r. The goal is to drive the error between the reference and the output to zero. It is common to add an integrator to the error signal and then minimize it. An alternative approach would be using the derivative of the error signal. Assuming perfect measurements:

$$\underline{x}_{error}(t) = \underline{x}_{ref}(t) - \underline{x}(t) \tag{17}$$

Taking the time derivative of the equation yields:

$$\dot{\underline{x}}_{error}(t) = \dot{\underline{x}}_{ref}(t) - \dot{\underline{x}}(t) \tag{18}$$

When the reference is predefined as constant, then $\dot{\underline{x}}_{ref}(t) = 0$, and

$$\dot{\underline{x}}_{error}(t) = -\dot{\underline{x}}(t) \tag{19}$$

A path tracking control law can be designed by using the following general relation:

$$\dot{\underline{x}}_{error}(t) = -\eta_i\dot{\underline{x}}(t), \quad i = 1, 2, ..., n \tag{20}$$

where η_i is an arbitrary constant representing the weight of the tracking performance in the cost function. In the matrix form, the above relation can written as:

$$\dot{\underline{x}}_{error}(t) = \begin{bmatrix} \dot{x}_{error}(t) \\ \dot{y}_{error}(t) \\ \dot{z}_{error}(t) \end{bmatrix} = \begin{bmatrix} -\eta_i\dot{x}(t) \\ -\eta_i\dot{y}(t) \\ -\eta_i\dot{z}(t) \end{bmatrix} \tag{21}$$

Substituting $\dot{x} = u, \dot{y} = v$ and $\dot{z} = w$, the above equation can be expressed as

$$\dot{\underline{x}}_{error}(t) = \begin{bmatrix} -\eta_i u(t) \\ -\eta_i v(t) \\ -\eta_i w(t) \end{bmatrix} \tag{22}$$

To accommodate the tracking term in the cost function, the state-space model is augmented as the following:

$$\dot{\underline{x}}_{aug}(t) = A_{aug}\underline{x}_{aug}(t) + B_{aug}\underline{u}(t) \tag{23}$$

where:

$$\underline{x}_{aug}(t) \;=\; \{x_{error}, y_{error}, z_{error}, \underline{x}\}^T \tag{24}$$

$$A_{aug} \;=\; \begin{bmatrix} 0_{3\times3} & -\eta.I_3 & 0_{3\times11} \\ 0_{14\times3} & & A \end{bmatrix} \tag{25}$$

$$B_{aug} \;=\; \begin{bmatrix} 0_{3\times4} \\ B \end{bmatrix} \tag{26}$$

When the terminal weighting is not considered, the performance measure is now

$$J = \frac{1}{2}\int_{t_0}^{t_f} [\underline{x}_{aug}(t)^T Q(t)\underline{x}_{aug}(t) + \underline{u}(t)^T R(t)\underline{u}(t)]dt \tag{27}$$

where the determination of the weighting matrices η, Q and R are empirical. Figs.3-4 show the results of implementing the LQR method for output tracking of model helicopter. More elaborate results are presented in Ref. [54]

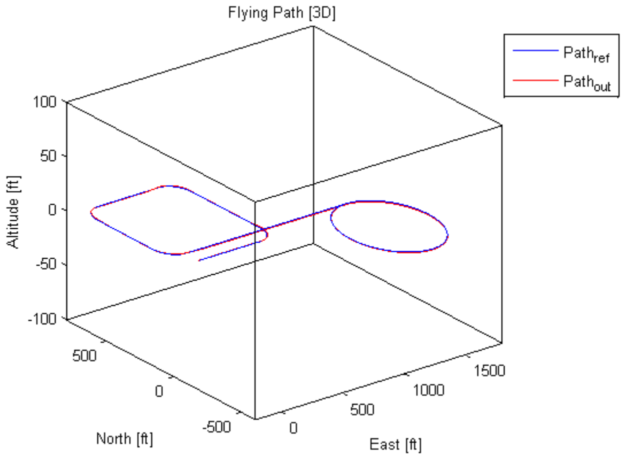


Fig. 3. Trajectory tracking performance, $\eta = 5, Q = I_{17}, R = I_4$

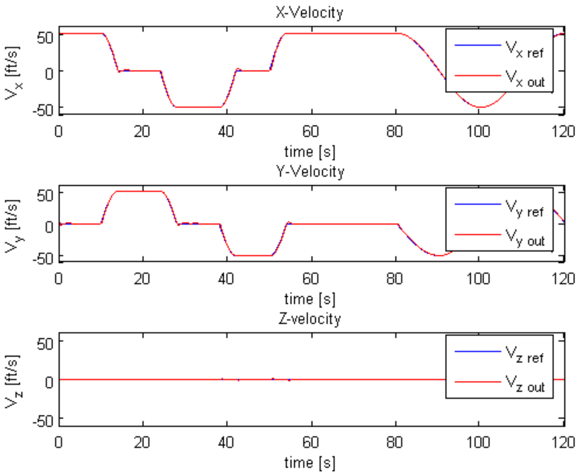


Fig. 4. Velocity tracking performance, $\eta = 5, Q = I_{17}, R = I_4$

Coefficient Diagram Method (CDM). CDM is a novel algebraic approach to a robust control design. Thus far CDM approach has been successfully applied primarily to single variable control synthesis. A very limited attempt has been made to extend its potential application to multivariable system. To the best of the author's knowledge, beyond the pioneering work by Manabe in [56] and [57], one of few recorded results for the attempt in this direction was the CDM application for steel mill drive control [58]. The present work extends the application of the CDM to MIMO control of model helicopter. In this study, CDM is implemented for a design of multivariable controller for a small scale helicopter during hover and cruise flight. In the synthesis of MIMO CDM, good design common sense based on hands-on experience is necessary. The low level controller algorithm is designed as part of hybrid supervisory control architecture to be implemented on an onboard computer system. Its feasibility and performance are evaluated based on its robustness, desired time domain system responses and compliance to hard-real time requirements. The results are presented in Figs.5-6. The numerical simulation shows that the CDM controller is robust to parameter variation and modeling uncertainties. The readers are referred to Ref.[55] for more complete explanation.

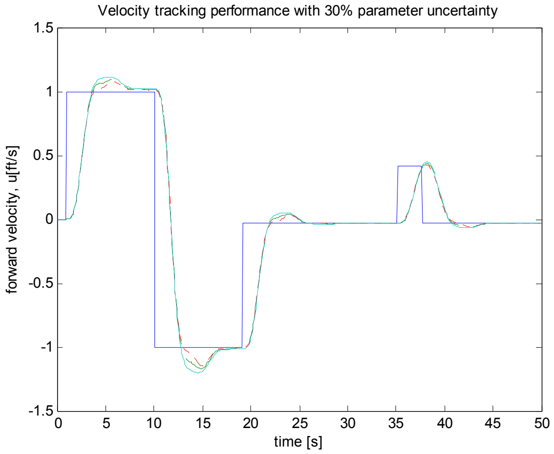


Fig. 5. The unit doublet response in the case of uncertainty in the X_u, X_a, M_u and M_w

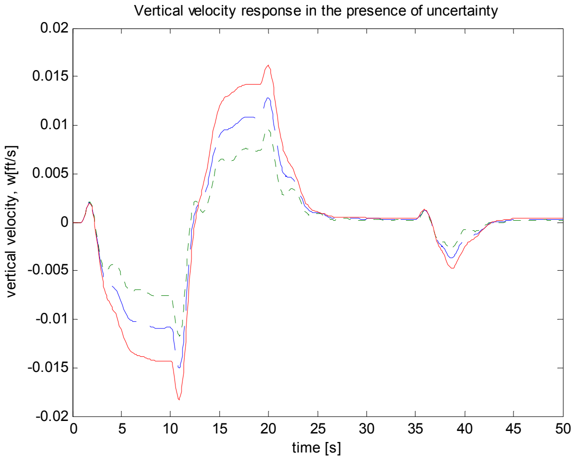


Fig. 6. The unit doublet response in the case of uncertainty in the X_u, X_a, M_u and M_w

D. *Navigation system*

The navigation system for the helicopter is based on the onboard inertial system. It is well-known that dead reckoning sensors such as INS, radar and terrain-aided navigation have high update rates but the errors are unbound. On the other hand, absolute sensors/position fixed such as GPS, Star-based and VOR-DME have fixed errors even though the update rates are generally low. To earn the benefit while eliminating weaknesses from both type of sensors, a sensor fusion using filtering technique can be designed. The ITB autonomous helicopter project includes the work on the filtering design to integrate INS and GPS measurements. Typical GPS signals used for navigation is updated at 1 Hz (with an accuracy of 10 m, 95% of the time) and in practice signal obstruction can happen. In the event of missing GPS signals, INS can give aiding data enabling the navigation system to coast along until GPS signal can be re-established. The entire GPS/INS can be viewed as INS aided by GPS system. The other form of aided information can also be provided by other source e.g. through the use of vehicle modeling. At present the study is focused on the viability of Kalman filter as means of state estimation algorithm. A mathematical model of GPS has been developed. The availability of the GPS model enables the performance of the Kalman Filter to be tested for various type of noise in the measured signals. In the next step, a variant of Kalman Filter called an Extended Kalman Filter will be designed to fuse the measurements of the two sensors. The study will also investigate the alternative to GPS/INS integration without the need to use Kalman filtering [59]. The performance and practicality of both approaches will be explored, compared and validated experimentally.

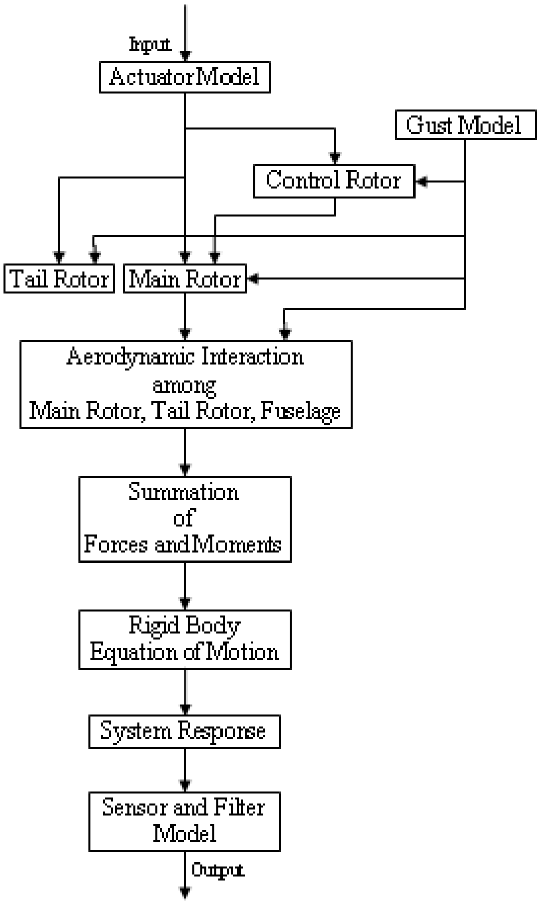


Fig. 7. Elements of Model Software [60]

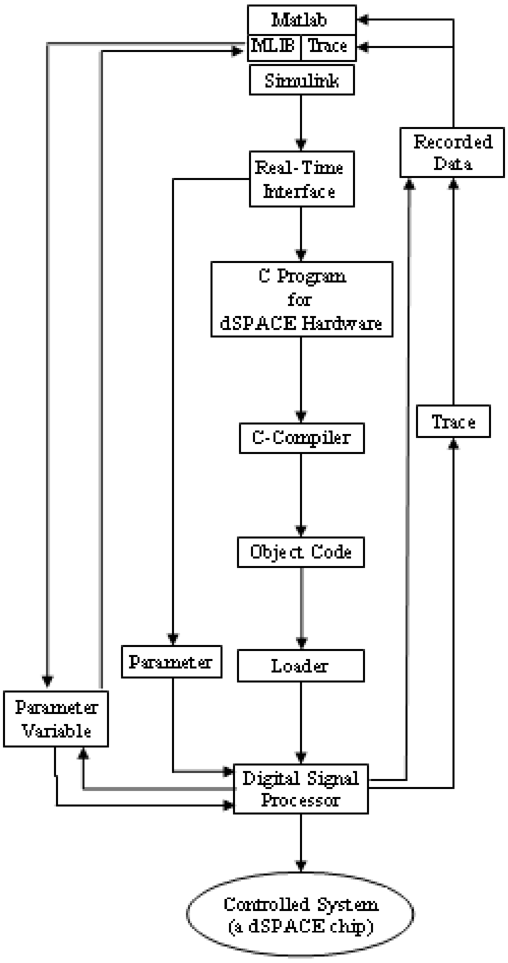


Fig. 8. HILS Modelling Procedure [60]

IV. EXPERIMENTAL SETUP

The ITB autonomous helicopter project is heavily experimental. An instrumented X-Cell-60 small scale helicopter is made available as the flying test-bed. Step-by-step autonomous system design procedure is carried out taking into account the risks associated with safety-critical system. A major effort has been focused on the development of Hardware-In-the-Loop simulation to facilitate the design, testing, and validation of real-time control and navigation system for the helicopter.

A. *Simulation approach*

The simulation facility consists of two different levels. The first level is the software simulation carried out within the MATLAB/Simulink environment. The virtual reality tool-box is used to develop a visualization of the helicopter motion with adequate fidelity. The virtual environment scenery is added to make the simulation closer to reality. Fig.9 illustrate the 3-D simulation of the helicopter developed at ITB. The second level of the simulation dealt with the hardware simulation. The HILS is developed to enable the accurate simulation of the time-dependent real signals.

In the HILs facility real-time controller can be tested by the use of dedicated digital signal processor (DSP) board. The work in this area deals with the integration of a nonlinear model of a small-scale helicopter along with the sensor and actuator models into a modular Simulink model described in Fig.7. The model was then uploaded into a dSPACE's DSP chip as illustrated in Fig.8. Based on that Simulink model, the DSP performed a real-time computing process and behaved like the represented helicopter dynamic system. The overall scheme of Hardware-In-the-Loop simulation system can play a significant role in the efficient control system design for aerial vehicles.

Fig. 9. Helicopter 3-D simulation

B. *Hardware development and integration*

The hardware development primarily consists of integration of onboard-computer system, ground control station and various sensors. At present a portable ground control station (GCS) is developed on the laptop. Fig.10 shows the typical screen-shot of the current GCS GUI design. The avionics system is presently being developed. The avionics box shown in Fig.11 includes a small scale GPS and IMU unit, flash-disk data storage and battery. The first trial test of the GPS system is given in Fig.12 showing GPS discrete data points plotted on the scaled map. The present effort is centered on improving the compactness of the avionics system such that upon the integration it will not substantially change the dynamics and stability of the helicopter.

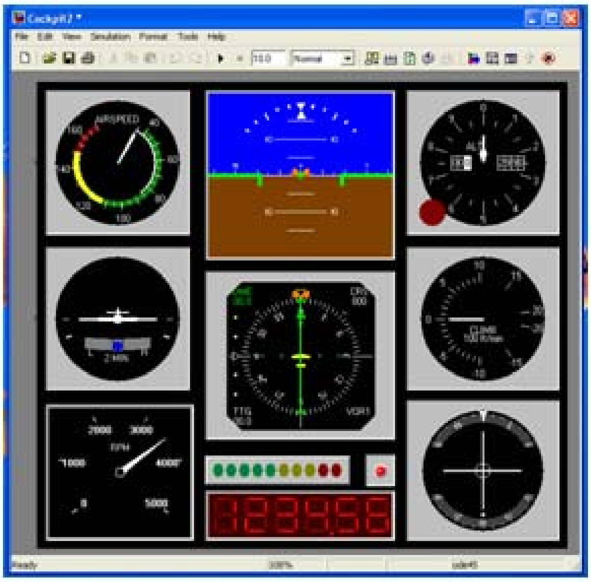


Fig. 10. Graphical user interface of the GCS Laptop

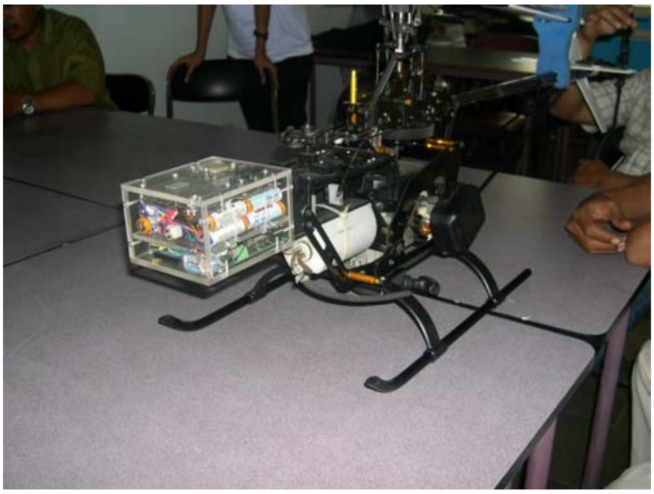


Fig. 11. Avionics box containing GPS, IMU, storage and power supply

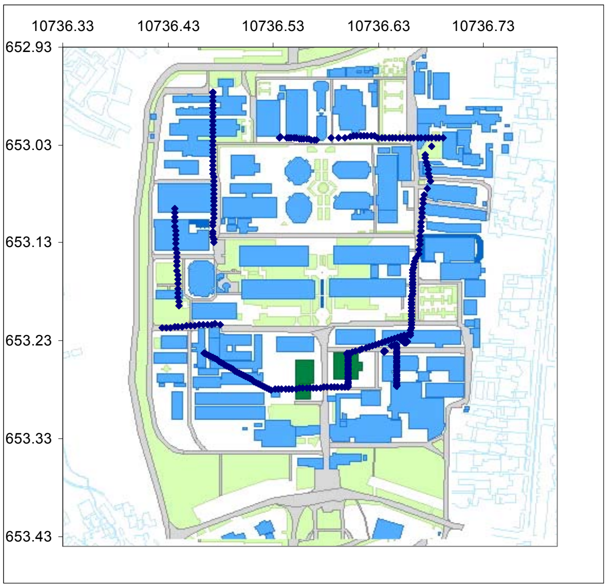


Fig. 12. Results of GPS data plots from the first avionics test

V. Current Status

The development of an autonomous helicopter at ITB is presently still in the early phase of the project years. Technology building blocks have been identified and milestones set to guide ongoing research activities (Fig.13). Major effort has been centered on the development of Hardware-in-the-loop simulation to facilitate near-reality simulation to reduce risks associated with safety-critical system and costs of flight tests. Most of the major elements of HILs have been developed. The ground control station system has been designed in accordance with the need of the mission. Meanwhile, initial tests have been conducted for the avionics system. Near term activities include the simulation and verification of control and navigation algorithm in the HILs facility, helicopter modeling refinement and on-board computer system design.

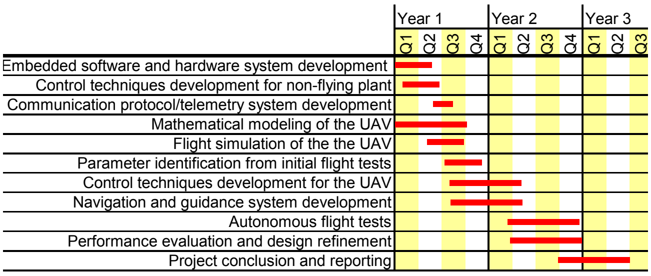


Fig. 13. Project milestones

VI. CONCLUDING REMARKS

The step by step autonomous helicopter system development has been presented. Primary technology building blocks have been identified and used for project planning. The autonomous system development is model-based and thus the early phase of research project has been focused on developing helicopter dynamics model. The Hardware-in-the-loop simulation is developed to facilitate the accurate simulation of time-dependent signals. The HILs is considered very essential in the entire process of safety-critical autonomous unmanned aerial vehicles development. Initial results in the optimal and robust control system development as well avionics system testing are reported.

Acknowledgment. The work was partially supported by the A2 Program Grant of the Directorate General of Higher Education. The author would like to acknowledge the support and participation of LAPAN hardware team for the development and testing of the avionics system. The helicopter 3-D simulation was largely developed by Singgih S Wibowo of the Department of Aeronautics and Astronautics, ITB.

REFERENCES

[1] V. Gavrilets, E. Frazzoli, B. Mettler, M. Piedmonte, and E. Feron, “Aggressive maneuvering of small autonomous helicopters. a human-centered approach,” *International Journal of Robotics Research*, pp. 795–807, October 2001.

[2] V. Gravilets, M. Martinos, B. Mettler, and E. Feron, “Control logic for automated aerobatic flight of miniature helicopter,” in *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, (Monterey, CA), August 2002.

[3] V. Gravilets, B. Mettler, and E. Feron, “Nonlinear model for a small-size acrobatic helicopter,” in *Proceedings of the AIAA Guidance, Navigation and Control Conference*, (Montreal, Canada), August 2001. Number AIAA 2001-4333.

[4] V. Gravilets, B. Mettler, and E. Feron, “Dynamic model for x-cell 60 helicopter in low advance ratio flight,” Tech. Rep. P-2543, MIT Laboratory for Information and Decision Systems, December 2002.

[5] V. Gravilets, A. Shterenberg, M. Dahleh, and E. Feron, “Avionics system for a small unmanned helicopter performing aggressive maneuvers,” in *Digital Avionics Systems Conference*, (Philadelphia, PA), October, 2000.

[6] E. Frazzolli, M. Dahleh, and E. Feron, “Real-time motion planning for agile autonomous vehicles,” *AIAA Journal of Guidance, Control and Dynamics*, vol. 25, pp. 116–129, 2002.

[7] V. Gravilets, A. Shterenberg, I. Martinos, K. Sprague, M. Dahleh, and E. Feron, “Avionics system for aggressive maneuvering,” *IEEE Aerospace and Electronic Systems Magazine*, pp. 38–43, September 2001.

[8] K. L. Sprague, “Design and validation of an avionics system for a miniature acrobatic helicopter,” Master’s thesis, Massachusetts Institute of Technology, Cambridge, MA, February 2002.

[9] K. Sprague, V. Gravilets, D. Dugail, B. Mettler, and E. Feron, “Design and applications of an avionics system for a miniature acrobatic helicopter,” in *AIAA Digital Avionics Systems Conference*, (Daytona Beach, FL), 2001.

[10] B. Mettler, M. Tischler, and T. Kanade, “System identification modeling of a small-scale unmanned rotorcraft for flight control design,” *Journal of the American Helicopter Society*, vol. 47, pp. 50–63, Jan 2002.

[11] V. Gravilets, *Autonomous Aerobatic Maneuvering of Miniature Helicopter*. PhD thesis, Massachusetts Institute of Technology, 2003.

[12] J. Toon, “Making UAVs smarter: Recent test demonstrates in-flight ability to reconfigure low-level control system autonomously.” Georgia Institute of Technology Research News, Georgia Tech Research News and Publications Office, July 1 2002.

[13] E. Johnson and S. Kanna, “Adaptive flight control for an autonomous unmanned helicopter,” *Proceedings of the AIAA Guidance, Navigation and Control Conference*, 2002.

[14] J. E. Corban, A. J. Calise, J. V. R. Prasad, J. Hur, and N. Kim, “Flight evaluation of adaptive high bandwidth control methods for unmanned helicopters,” in *Proceedings of the AIAA Guidance, Navigation and Control*, American Institute of Aeronautics and Astronautics, 2002.

[15] J. Ditrich and E. Johnson, “Multi-sensor navigation system for an autonomous helicopter,” *Digital Avionics System Conference*, 2002.

[16] E. Johnson and S. Fontaine, “Use of flight simulation to complement flight testing of low-cost UAVs,” *AIAA Modeling and Simulation Technologies Conference*, 2001.

[17] J. Ditrich, “Design and integration of an unmanned aerial vehicle navigation system,” Master’s thesis, School of Aerospace Engineering, Georgia Tech, May 2002.

[18] E. Johnson, P. DeBitteto, C. Trott, and M. Bosse, “The 1996 MIT/Boston University/Draper laboratory autonomous helicopter system,” *15th AIAA/IEEE Digital Avionics System Conference*, vol. 1, 1996.

[19] E. Johnson and P. DeBitteto, “Modeling and simulation for small autonomous helicopter development,” *AIAA Modeling and Simulation Technologies Conference*, 1997. Monterey, California.

[20] N. Hovakimyan, N. Kim, and A. J. Calise, “Adaptive output feedback for high-bandwidth control of an unmanned helicopter,” *AIAA Guidance, Navigation and Control Conference*, 2000. AIAA-2000-4058.

[21] M. G. Perhinschi and J. V. R. Prasad, “A simulation model of an autonomous helicopter,” Georgia Tech.

[22] E. Johnson and D. P. Schrage, “System integration and operation of a research unmanned aerial vehicle,” Georgia Tech.

[23] E. Johnson, S. Fontaine, and A. Kahn, “Minimum complexity uninhabited air vehicle guidance and flight control system,” Georgia Institute of Technology.

[24] R. Kornfeld, *The Impact of GPS Velocity Based Flight Control on Flight Instrumentation Architecture*. PhD thesis, Massachusetts Institute of Technology, 1999.

[25] O. Amidi, T. Kanade, and J. R. Miller, “Autonomous helicopter research at carnegie mellon robotics institute,” *Proceedings of Heli Japan ’98*, Apr 1998.

[26] O. Amidi, T. Kanade, and R. Miller, “Vision-based autonomous helicopter research at carnegie mellon robotics institute,” *Proceedings Heli Japan ’98*, 1998. Gifu, Japan.