Autopilot Design of Tilt-rotor UAV
Using Particle Swarm Optimization Method
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Abstract: This paper describes an autopilot design of tilt-rotor UAV, which is being developed by KARI as a Smart UAV Development Program in Korea, using particle swarm optimization (PSO) method. The tilt-rotor UAV considered in this paper holds five control modes in the stability and control augmentation system (SCAS) depending on flight mode. Flight control systems designed via the classical approach have been performed in such a way that yields linear models about several trim flight conditions, designing linear controllers for each condition, and integrating these design points with a gain scheduling scheme. However, it is very tedious and time-consuming to design an autopilot of a tilt-rotor UAV which represents various dynamic characteristics, nonlinearity, and uncertainty via classical control technique, because there are many design points and operating conditions throughout the flight envelope. To solve this problem, an automatic tool for control system design using PSO method is developed and applied to autopilot design of tilt-rotor UAV. The desired output of control system is chosen to satisfy the control system requirement. Gain margin and phase margin of control system are additionally considered as a penalty term in the objective function. The designed control system guarantees the satisfaction of the control system requirement ensuring a sufficient stability margin of the control system. Also, the gain scheduling scenario and SCAS switching logic of each control mode are successfully designed. Fully nonlinear 6-DOF simulation for an automatic landing scenario is performed to verify the performance of autopilot system of tilt-rotor UAV. The results from the nonlinear simulation show good control performance of the tilt-rotor UAV.

Keywords: Tilt-rotor UAV, Autopilot Design, Particle Swarm Optimization

1. INTRODUCTION

This paper describes an autopilot design of a tilt-rotor UAV, which is being developed by KARI as a Smart UAV Development Program in Korea, using particle swarm optimization (PSO) method. Tilt-rotor UAV features the hovering performance of a helicopter and cruising performance of a turboprop airplane according to a change in the tilt angle of wing tip mounted prop-rotors. The conversion of flight modes between helicopter and airplane configurations necessitates a different control strategy. The tilt-rotor UAV considered in this paper holds six control modes in the stability and control augmentation system (SCAS) depending on flight modes. Ground, inertial velocity, and forward modes are contained in helicopter flight mode conversion or RPM conversion modes in conversion flight mode and airplane mode in airplane flight mode. The control architecture of SCAS in longitudinal and lateral channels and the role of four control sticks; collective, longitudinal cyclic, lateral cyclic, and pedal, are different in each control mode.

The classical control technique has been widely studied and successfully applied to aircraft flight control systems. Flight control systems designed via the classical approach have been performed in such a way to yield linear models about several trim flight conditions, designing linear controllers for each condition, and integrating these design points with a gain scheduling scheme. However, it is very tedious and time-consuming to design an autopilot for tilt-rotor UAV which represents various dynamic characteristics, nonlinearity, and uncertainty via classical control technique, because there are many design points and operating conditions throughout the flight envelope. To solve this problem, an automatic tool for control system design using PSO method is developed and applied to autopilot design of tilt-rotor UAV. PSO is one of the simplest and fastest optimization algorithms. It shows some similarity with evolutionary algorithms except for reproduction and mutation processes. In this process, the controller gain set of each control mode is determined to minimize the objective function which is the sum of square error between the desired output and actual output of control system. The desired output of the control system is chosen to satisfy the control system requirement. Gain margin and phase margin of control system are additionally considered as a penalty term in the objective function. The designed control system guarantees the satisfaction of the control system requirement ensuring a sufficient stability margin of the control system. Also, gain scheduling scenario and SCAS switching logic of each control mode are successfully designed. Fully nonlinear 6-DOF simulation for an automatic landing scenario is performed to verify the performance of autopilot system.
of tilt-rotor UAV. The results from the nonlinear simulation show good control performance of tilt-rotor UAV.

2. PSO ALGORITHM

The particle swarm optimization (PSO) has been successfully applied in function optimization problems. In this paper, we attempted to obtain the gain of linear controller by converting an autopilot design problem to a parameter optimization problem.

The PSO is one of the evolutionary computation techniques introduced by Kennedy and Eberhart in 1995 [3]. The PSO algorithm is similar to evolutionary computation in producing a random population initially and generating the next population based on current cost, but it does not need reproduction or mutation to produce the next generation. Thus, PSO is faster in finding solutions compared to any other evolutionary computation technique. In the PSO algorithm, each particle is moving, and hence has a velocity. Also, each particle remembers the position it was in and where it had its best result so far. Moreover, the particles in the swarm co-operate exchanging information about what they have discovered in the search region they have visited. The basic PSO algorithm can be summarized as follows;

2.1 Basic PSO Algorithm

1. Initialize a population of particles with random position and velocity,

   \[ x_i^0 = x_{min} + \text{rand} \times (x_{max} - x_{min}) \]
   \[ v_i^0 = v_{min} + \text{rand} \times (v_{max} - v_{min}) \]  

2. For each particle, evaluate the fitness value.

3. Compare a particle’s fitness evaluation with particle’s pbest \((p_i^k)\). Exchange the particle’s fitness value and position with pbest, if it is better.

4. Compare a particle’s fitness evaluation with the population’s overall previous best, gbest \((p_g^k)\). Exchange the particle’s fitness value and position with gbest, if it is better.

5. Update the velocity and the position of the particle according to following update equations.

   \[ v_i^{k+1} = w v_i^k + c_1 r_1 (p_i^k - x_i^k) + c_2 r_2 (p_g^k - x_i^k) \]
   \[ x_i^{k+1} = x_i^k + v_i^{k+1} \]  

6. Loop to step 2 until the given criterion is met.

In the velocity update equation of Eq. (2), \(w\), \(c_1\), and \(c_2\) mean inertia weight, self and swarm confidence factors, respectively. Also, \(r_1\), and \(r_2\) are random numbers on the interval \([0, 1]\).

2.2 Formulation of Performance Index

The PSO algorithm has been developed that uses a numerical optimization method. In general, parameters to optimize are evaluated by performance index in the numerical optimization method. Therefore, the way of defining the performance index effect on the optimized results considerably. In order to evaluate optimal control gains that satisfy performance requirements of the control system, the cost function is evaluated as following expression.

\[ J = \int_{t_0}^{t_f} W(t)(y_{ref} - y_{out})^2 dt + \sum_{i=1}^{n} W_i c_i \]  

Where \(y_{ref}\) is the reference which is considered the performance requirements of control system, \(y_{out}\) is the output of the real system and \(W(t)\) is the weight function. At this time, the reference is set to represent response characteristics of the second order system with the required damping and frequency. \(W_i\) and \(c_i\) are constraints and weights respectively. That is added with the cost function as a penalty term. The constraints in Eq. (3) can be set by a designer. This representation would be useful for problems the parameters to be determined can be solved in time domain with system response.

Our proposed algorithm in this paper can deal with various constrains that are gain margin, phase margin, rising time, maximum overshoot and requirements of handling qualities, etc.
3. APPLICATION TO AUTOPILOT DESIGN OF TILT-ROTOR UAV

3.1 Tilt-Rotor UAV
The tilt-rotor UAV has been developed by Korea Aerospace Research Institute (KARI) for a robust and intelligent tilt rotor UAV exhibiting high-speed cruise and vertical take-off and landing capabilities since 2002. The tilt-rotor UAV shown in figure 2 will perform various civil missions including disaster detection and management, weather forecasting, and environmental monitoring, etc.

Fig. 2 Tilt-Rotor Unmanned Aerial Vehicle (Smart UAV)

For reference, the Smart UAV controls operate as shown in figure 3.

(a) helicopter mode       (b) airplane mode

Pitch: Longitudinal Cycle
Elevator

Thrust: Differential Collective Pitch and Lateral Cycle

Roll: Differential Longitudinal Cycle

Yaw: Differential Collective Pitch without Rudder

Longitudinal Cyclic
Collective Pitch with Rotor Governing

Differential Collective Pitch and Lateral Cycle

Aileron with Differential Collective Pitch for ARI

In helicopter mode, pitch control is archived through longitudinal cyclic, roll control through both differential collective pitch and lateral cyclic, yaw through differential longitudinal cyclic and heave through collective pitch with rotor governing. In conversion mode, the rotor controls are gradually blended out. In airplane mode, tilting control is locked out.

3.2 Autopilot Design of Smart UAV
In the autopilot design problem, it is difficult to systematically determine the controller gain satisfying the required performance and guaranteeing sufficient stability. This problem may be easily treated by applying the parameter optimization technique, especially where the control system architecture is predetermined and the controller is a linear controller. In this approach, all particles, which are essentially controller gain candidates, fly to minimize the cost function defined by the sum of square errors between the desired response and the actual response of a plant. At this moment, stability requirements are dealt with and constraints are included in the cost function as a penalty function.

The proposed approach has some advantages in directly handling nonlinear dynamics and easily changing the structure of autopilot systems. In this section, we design an attitude-hold autopilot for tilt-rotor UAV applying the proposed method.

Figure 4 and figure 5 are the attitude-hold autopilot configuration of the pitch and the roll axis respectively for the Smart UAV.

In this problem, the total number of controller gains to be determined in pitch axis is 4; \(K_q, K_\theta, K_p, \) and \(K_I\).

The desired output of attitude-hold autopilot is in Eq. (4) and the cost function and constraints are shown in Eq. (5).

\[
y_{\text{ref}}(s) = \frac{\omega_0}{s^2 + 2\zeta \omega_n s + \omega_n^2}
\]
\[
\zeta \geq 0.7
\]
\[
3.0 \text{ rad/s} \leq \omega_n \leq 4.0 \text{ rad/s}
\]
\[
J = (y_{\text{ref}} - y_{\text{out}})^2 + \sum_{i=1}^{3} w_i g_i
\]
\[
g_1 : GM \geq 7\text{dB}
\]
\[
g_2 : PM \geq 45\text{deg}
\]
The control performance of attitude-hold and linear velocity hold (DP-02) autopilots in pitch and roll axis are shown in figure 6 and figure 7 respectively. The DP-02 is the inertial velocity mode in the helicopter mode in which the longitudinal and lateral control stick inputs command control the forward and lateral velocity of the aircraft. And the others are the attitude-hold autopilot modes in helicopter mode.

The blue and the cyan lines represent a design requirements boundary of natural frequency and damping ratio. The red line represents the time response of pitch angle. From the results, autopilot with PI controller and with controller gains determined by the proposed method, shows satisfactory performance. Also, autopilot with a different type controller can be easily designed by the proposed approach.

Figure 8 shows a stability margin of the all flight mode in pitch and roll axis. Note that the design requirements of the gain margin and phase margin are over 7dB and over 45deg. From the results, the stability margin meets the design requirement in all flight mode using the particle swarm optimization method.

<table>
<thead>
<tr>
<th>Aircraft Config</th>
<th>Control Mode</th>
<th>Vel. (kph)</th>
<th>Thr. Angle (deg)</th>
<th>Eng. RPM (rpm)</th>
<th>Pitch Axis G.M. (dB)</th>
<th>P.M. (deg)</th>
<th>Roll Axis G.M. (dB)</th>
<th>P.M. (deg)</th>
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<tr>
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<td>45.0</td>
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<tr>
<td></td>
<td>PM</td>
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<td>90</td>
<td>5630</td>
<td>5.5</td>
<td>45.1</td>
<td>9.2</td>
<td>45.3</td>
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<tr>
<td></td>
<td>FM</td>
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<td>90</td>
<td>5630</td>
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<td>9.4</td>
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<td></td>
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<td>11.3</td>
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</tr>
</tbody>
</table>

4. CONCLUSIONS

In this paper, we proposed a method for tilt-rotor UAV autopilot design by parameter optimization technique. Moreover, autopilots for tilt-rotor UAV were designed by applying the proposed method. From the analysis of design results, we conclude that the proposed method is a more efficient and flexible technique in autopilot design problems. From the autopilot design of tilt-rotor, the following observation and conclusions can be drawn:

- The autopilot of Smart UAV has been designed successfully using the particle swarm optimization (PSO) method.
- The proposed approach has a advantages in directly handling nonlinear dynamics and easily changing the structure of autopilot systems.
- The stability margin of the Smart UAV meets the design requirement in all flight mode using the particle swarm optimization method.

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REFERENCES


