Situational Awareness based Neural Flight Control of a Coaxial Rotor/Ducted-Fan Helicopter

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Abstract: - This paper focuses on a critical component of the situational awareness (SA), the control of autonomous vertical flight for the coaxial rotor/ducted-fan helicopter (CRDFH). Autonomous vertical flight is a challenging but important task for CRDFHs to achieve high level of autonomy under adverse conditions. With the SA strategy, we proposed a neural flight control procedure to address the dynamics variation and performance requirement difference in initial and final stages of flight trajectory for a nontrivial CRDFH type model. This control strategy for chosen mini-helicopter model has been verified by simulation of take-off and hovering maneuvers using software package Simulink and demonstrated good performance for fast SA in real-time search-and-rescue operations.

Key-Words: - Coaxial rotor/ducted-fan helicopter, flight control, NARMA-L2 neurocontroller, simulation, situational awareness.

1 Introduction
Situation awareness has been formally defined as “the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future” [2]. As the term implies, situation awareness refers to awareness of the situation. Grammatically, situational awareness (SA) refers to awareness that only happens sometimes in certain situations.

SA has been recognized as a critical, yet often elusive, foundation for successful decision-making across a broad range of complex and dynamic systems, including emergency response and military command and control operations [3].

The term SA have become commonplace for the doctrine and tactics, and techniques in the U.S. Army [4]. SA is defined as “the ability to maintain a constant, clear mental picture of relevant information and the tactical situation including friendly and threat situations as well as terrain”. SA allows leaders to avoid surprise, make rapid decisions, and choose when and where to conduct engagements, and achieve decisive outcomes.

The coaxial rotor/ducted-fan helicopter (CRDFH) is one of the key tools to gather the information to build SA for all leaders. The CRDFH is the ground maneuver commander's primary day and night system. The CRDFH provides the commander with a number of capabilities including:
- Enhanced SA.
- Target acquisition.
- Battle damage assessment.
- Enhanced battle management capabilities (friendly situation and battlefield visualization).

The combination of these benefits contributes to the commander's dominant SA allowing him to shape the battlefield to ensure mission success and to maneuver to points of positional advantage with speed and precision to conduct decisive operations.

Some conditions for conducting aerial reconnaissance with CRDFHs are as follows:
- Time is limited or information is required quickly.
- Detailed reconnaissance is not required.
- Extended duration surveillance is not required.
- Target is at extended range.
- Threat conditions are known; also the risk to ground assets is high.
- Verification of a target is needed.
- Terrain restricts approach by ground units.

The CRDFH offers many advantages, including low cost, the ability to fly within a narrow space and the unique hovering and vertical take-off and landing (VTOL) flying characteristics.
The current state of CRDFHs throughout the world is outlined [7]. A novel design of a multiple rotary wing platform which provide for greater SA in the urban terrain is then presented.

Autonomous vertical flight is a challenging but important task for CRDFHs to achieve high level of autonomy under adverse conditions. The fundamental requirement for vertical flight is the knowledge of the height above the ground, and a properly designed controller to govern the process.

In [1], a three stage flight control procedure using three autonomous control subsystems for a nontrivial nonlinear helicopter model on the basis of equations of vertical motion for the center of mass of helicopter was proposed. The proposed control strategy has been verified by simulation of hovering maneuvers using software package Simulink and demonstrated good performance for fast SA.

This paper concentrates on issues related to the area of [1], but demonstrates another field for application of these ideas, i.e., research technique using control system modeling and simulation on the basis of equations of motion for the center of mass of small CRDFH for fast SA.

In this paper our research results in the study of vertical flight (take-off and hovering cases) control of small CRDFH which make such SA task scenario as “go-search-find-return” possible are presented.

The contribution of the paper is twofold: to develop new schemes appropriate for SA enhancement using CRDFHs by control of vertical flight of small CRDFHs in real-time search-and-rescue operations, and to present the results of hovering maneuvers for chosen model of CRDFH for fast SA in simulation form using the MATLAB/Simulink environment.

2 CRDFH Model

The CRDFH has a coaxial rotor/ducted-fan configuration and has an axial symmetric with respect to the rotation shaft. It is mainly composed of five components: teetering rotor, ducted fan, duct fuselage, engine and landing gear. A fan is nested in the duct fuselage in order to produce anti-torque as well as part of lift. The rotor and the ducted fan counter rotate about the shaft at the same speed.

The dynamics of CRDFH for the case of low speeds of motion can be represented by the following equations [8]

\[
\dot{x}(\tau) = Ax(\tau) + Bu(\tau) + \nu(\tau) \\
y(\tau) = Cx(\tau) + \omega(\tau)
\]

where \(x(\tau), u(\tau), y(\tau), \nu(\tau), \omega(\tau)\) are the state, control input, output, process noise and measurement noise vectors, respectively.

The variables of this model are:

\[
x = \begin{bmatrix} u \\ v \\ w \\ p \\ q \\ r \\ \phi \\ \theta \\ \psi \end{bmatrix}, \quad u = \begin{bmatrix} \delta_{MR} \\ \delta_{lat} \\ \delta_{lon} \\ \delta_{DF} \end{bmatrix},
\]

where \(u, v, w\) are surge, sway and heave velocities; \(p, q, r\) are angular velocities of roll, pitch and yaw motions; \(\phi, \theta, \psi\) are roll, pitch and yaw angles; \(\delta_{MR}, \delta_{lat}, \delta_{lon}, \delta_{DF}\) are main rotor collective, lateral cyclic, longitudinal cyclic and ducted fan collective pitches.

The matrix structure of \(A, B, C\) for the state-space model of system (1)-(2) is given by

\[
A = \begin{bmatrix}
  a_1 & a_2 & 0 & a_4 & 0 & 0 & a_5 & 0 \\
  a_6 & a_7 & 0 & a_8 & a_9 & 0 & a_{10} & 0 \\
  0 & 0 & a_{11} & 0 & 0 & 0 & 0 & 0 \\
  a_{13} & a_{14} & 0 & a_{15} & a_{16} & 0 & 0 & 0 \\
  a_{17} & a_{18} & 0 & a_{19} & a_{20} & 0 & 0 & 0 \\
  0 & 0 & a_{21} & 0 & 0 & a_{22} & 0 & 0 \\
  0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
\end{bmatrix}
\]
The parameters $a_i$ through $a_{22}$ and parameters $b_i$ through $b_{12}$ in (4) are given by:

$$
\begin{align*}
  a_1 &= 0.0060, & a_2 &= 0.0030, & a_3 &= 0.0080, \\
  a_4 &= 0.0330, & a_5 &= -9.8000, & a_6 &= -0.0030, \\
  a_7 &= -0.0060, & a_8 &= -0.0330, & a_9 &= 0.0080, \\
  a_{10} &= 9.8000, & a_{11} &= -0.9820, & a_{12} &= 0.0800, \\
  a_{13} &= -0.0070, & a_{14} &= -0.0150, & a_{15} &= -0.0870, \\
  a_{16} &= 0.0210, & a_{17} &= 0.0110, & a_{18} &= -0.0050, \\
  a_{19} &= -0.0150, & a_{20} &= -0.0600, & a_{21} &= -0.0050, \\
  a_{22} &= -0.1700; \\
  b_1 &= 2.1290, & b_2 &= -2.8850, & b_3 &= -0.5206, \\
  b_4 &= 9.9930, & b_5 &= -122.0160, & b_6 &= -11.8690, \\
  b_7 &= -7.5960, & b_8 &= -5.6080, & b_9 &= -3.8580, \\
  b_{10} &= 5.2260, & b_{11} &= 26.0030, & b_{12} &= -10.7720.
\end{align*}
$$

The derivative of attitude vector $(x, y, z)^T$ for center of mass of CRDFH can be described in a common way through next expression as indicated in [5]

$$
\begin{align*}
  \dot{x} &= j_{11} u + j_{12} v + j_{13} w, \\
  \dot{y} &= j_{21} u + j_{22} v + j_{23} w, \\
  \dot{z} &= j_{31} u + j_{32} v + j_{33} w,
\end{align*}
$$

where

$$
\begin{align*}
  j_{11} &= \cos(\psi) \cos(\theta), \\
  j_{12} &= -\sin(\psi) \cos(\phi) + \cos(\psi) \sin(\theta) \sin(\phi), \\
  j_{13} &= \sin(\psi) \sin(\phi) + \cos(\psi) \cos(\phi) \sin(\theta), \\
  j_{21} &= \sin(\psi) \cos(\theta), \\
  j_{22} &= \cos(\psi) \cos(\phi) + \sin(\phi) \sin(\theta) \sin(\psi), \\
  j_{23} &= -\cos(\psi) \sin(\phi) + \sin(\theta) \sin(\psi) \cos(\phi), \\
  j_{31} &= -\sin(\phi), \\
  j_{32} &= \cos(\theta) \sin(\phi), \\
  j_{33} &= \cos(\theta) \cos(\phi).
\end{align*}
$$

Then, we have

$$
\begin{align*}
  x(\tau) &= \int_0^\tau \dot{x}(t) dt, \\
  y(\tau) &= \int_0^\tau \dot{y}(t) dt, \\
  z(\tau) &= \int_0^\tau \dot{z}(t) dt,
\end{align*}
$$

where $x(0) = 0, y(0) = 0, z(0) = 0$.

From (1)-(6) we can see that the attitude vector $(x, y, z)^T$ for given model of the CRDFH can be computed.

### 3 Simulation Results

Consider the control of given CRDFH model (1)-(2) for the case of take-off and hovering maneuvers.

The goal of the following simulations is twofold. First, we verify that this control system is able to control the take-off and hovering trajectories. Second, we observed the effect of enhancing SA because the variety of such trajectory parameter as main rotor collective pitch easily can be changed the possible take-off and hovering trajectories of given CRDFH.

Initial conditions and desired height for control system are chosen to be:

$$
\begin{align*}
  x(0) &= y(0) = z(0) = 0, & \theta(0) = 14m.
\end{align*}
$$

Simulation results of the offered block scheme with one control system (see Fig. 1) are shown in Figs. 2-6.

In [6], the two approximations to the nonlinear autoregressive moving average (NARMA) model called the NARMA-L1 and the NARMA-L2 are proposed. From a practical stand-point, the NARMA-L2 model is found to be simpler to realize than the NARMA-L1 model.

The neurocontroller used in this section is based only on the NARMA-L2 approximate model [6].

Some advantages of this example are as follows.

- Possibility to consider a terrain restriction in a place of a hovering.
- Possibility of lag in different selected height positions.
- Using of one control system to control the take-off and hovering trajectories of flight.
Fig. 1. Block diagram of control system.

Fig. 2. Height trajectory of motion control.

Fig. 3. X-Y view of CRDFH’s trajectory.
Fig. 4. X-Z view of CRDFH’s trajectory.

Fig. 5. Y-Z view of CRDFH’s trajectory.

Fig. 6. 3-D motion of CRDFH.
4 Conclusions
A new research technique is presented in this paper for enhanced SA in possible CRDFH’s missions.

The need for highly reliable and stable hovering for VTOL class CRDFHs has increased morbidly for critical situations in real-time search-and-rescue operations for fast SA.

The effectiveness of the proposed flight strategy has been verified in field of flight simulation tests for chosen model of CRDFH using software package Simulink.

From the simulation studies of flight tests, the following can be observed:
- The NARMA-L2 Controller tuning can be accomplished quickly and accurately using internal windows for this block.
- The trajectory tracking display forms give a researcher an immediate view of given CRDFH motion with a range of such parameter as main rotor collective pitch. This allows us to investigate the sensitivity of the control system, providing a medium for such development and evaluation and enhancing the researcher’s understanding of take-off and hovering maneuvers.

From the applications viewpoint, we believe that this flight strategy using flexible and effective control furnishes a powerful approach for enhancing SA in applications to VTOL class CRDFHs.

Future work will involve further validation of the performance of the proposed research technique and exploring other relevant and interesting CRDFH’s missions.

References: