Automatically Landing a Helicopter on a Moving Ship

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Abstract: UMS Skeldar is a Saab company developing the unmanned helicopter Skeldar V-200, a remotely piloted aerial system designed for a wide range of naval military applications. A key feature of the Skeldar V-200 is the capability to perform automatic take-off and landing on a moving ship. In this presentation we describe the challenges of this task and outline the technical solution developed at UMS Skeldar. In particular, we show how Kalman filtering and feedforward control can be used to adapt to the vertical motion of the ship deck due to waves, to achieve a smooth landing. Results from recent flight tests are used to illustrate the solution.

1. INTRODUCTION

In several European countries, naval fleets are currently being modernized. A common requirement is to have an unmanned aerial system (UAS) with vertical take-off and landing (VTOL) capability onboard. At UMS Skeldar in Linköping, we are meeting this demand with our product Skeldar V-200, consisting of an unmanned helicopter controlled from a remote pilot station (RPS) to be integrated into customer ships.

Performing automatic take-off and landing (ATOL) from a ship in forward motion, subjected to wind and waves, is a challenging control task. In this contribution, we outline the technical solution developed at UMS Skeldar in terms of signal processing and control algorithms. We will focus on the landing case, since this is the most challenging task.

2. CONTROL STRATEGY DURING LANDING

A ship travelling at sea moves in six degrees-of-freedom. The three translational motions are surge (forward/aft), sway (sideways) and heave (up/down). The three rotational motions are pitch (bow up/down), roll (side-to-side rotation) and yaw (bow left/right). Roughly speaking, the Skeldar V-200 control strategy for automatic landing is

a) to follow the mean forward motion of the ship (not attempting to adjust to temporary variations in ship pitch, roll, yaw, surge or sway)

b) while taking the ship heave motion into account during descent towards deck when landing is commanded (to achieve a smooth touchdown)

The design is such that a remote pilot can land the helicopter on deck with minimal effort and piloting skills.

After an approach has been made to a position behind the ship, the Skeldar-200 can be "tethered" to the ship. When tethering is activated, the helicopter will automatically follow the forward motion of the ship, using information from a navigation system mounted on the ship. To an observer on the ship, this means that the helicopter enters hover relative to the ship. The pilot can then use high-level control commands to make the helicopter enter hover directly above the helipad, i.e. the landing area typically located at the aft of the ship.

From this position, the pilot can command landing by pressing a button. To achieve a smooth landing with low impact energy at touchdown, it is important for the flight control system to consider the vertical heave motion of the helipad, typically located at the aft of the ship. In the V-200, this feature is known as "heave compensation".

3. HEAVE COMPENSATION

The heave motion of a ship helipad typically has a strong periodic component, but the amplitude (and phase) will vary over time. The time period varies a lot depending on which sea the ship is travelling in.

By sending ship navigation data via the data link, the helicopter continuously gets information about the helipad motion, including the vertical velocity, i.e. the heave rate.

Feeding the heave rate alone to the controller for the vertical helicopter motion results in an unacceptable phase lag between the vertical motion of the ship and the helicopter. For the Skeldar V-200, this is solved by also estimating the heave acceleration. Using the helipad heave acceleration for feed-forward control solves the phase lag problem.

A numerically robust way of estimating the helipad acceleration based on velocity measurements, with low signal noise and phase lag, is as follows. Locally in time, the heave rate can be modelled as

$$v = A\sin(\omega t + \phi)$$

where the amplitude A, angular frequency ω and phase ϕ will vary over time. Neglecting these variations, we can express the vertical acceleration and jerk (acceleration time derivative) as

$$a = \dot{v} = \omega A\cos(\omega t + \phi)$$
$$j = \dot{a} = -\omega^2 A\sin(\omega t + \phi) = -\omega^2 v$$

This leads to the following Kalman filter formulation in terms of state dynamics and measurement equation:

$$\frac{d}{dt}\begin{pmatrix} v \\ a \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ -\omega^2 & 0 \end{pmatrix}\begin{pmatrix} v \\ a \end{pmatrix} + \begin{pmatrix} 0 \\ 1 \end{pmatrix} w$$

$$y = v + e$$

with process noise w and measurement noise e. This can be used to design a discrete-time Kalman filter taking heave rate measurements as input and estimating filtered heave rate, acceleration and jerk with low noise content as well as low phase lag.

The angular frequency ω can be estimated from heave rate measurements using a zero-crossing algorithm.

This filter along with feedforward control of estimated signals has been implemented into the Skeldar V-200 flight control system. Successful flight testing has been performed using a large-scale motion platform to simulate the dynamic motion of a helipad on a ship in rough sea.

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