

LP Based Path Planning for Autonomous Landing of An Unmanned Helicopter on A Moving Platform

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Abstract— Autonomous landing of an unmanned helicopter (UH) on a moving platform can greatly expand its application field. In this paper, a path planning method based on linear programming (LP) is proposed in the relative coordination to finish the autonomous landing task. First, the landing procedure is divided into four stages. Then, the linear constraints in each stage are established respectively which include helicopter's flight envelope constraints and target kinematic constraints. Based on the established LP formulations, the flight control system's optimal velocity expectation is derived. A simulation system based on FlightGear and Matlab is established and used as the validation platform for this approach, the simulation results demonstrate the effectiveness and efficiency of this approach and the real flight test is under development.

Keywords—autonomous landing, LP, moving platform, UH

I. INTRODUCTION

Unmanned Helicopters(UHs), with the special capability of vertical takeoff and landing, hovering, lateral free moving, can be used in many scenarios where fix wing unmanned aircrafts are difficult to finish the tasks such as longtime surveillance at a fix point, low altitude flight in urban city for anti-terrorism mission etc. But the high maneuverability of UHs comes at a significant cost of unstable and dangerous to fly [1]. This proposes a challenging mission for researchers to build an autonomous flight control system such that the UH system can be easy and stable to use.

Autonomous landing is a crucial capability for an UH to finish any mission. In [1], a real time vision system is built up based on a cooperative landing target, the image processing algorithm could be greatly simplified and accuracy of the location is greatly increased. The accuracy of this vision system is within 40cm in position and 7 degree in orientation. Autonomous landing is finished using the behavior-based controller by following a path to the landing site based on the landing parameters derived from the vision system. In [2], a

different vision cooperative landing target is proposed and verified in flight test with the accuracy up to 5cm in position and 5 degree in orientation, the landing task is finished in a different control framework as a hierarchical flight management system. In [13], a lidar-based landing zone perception system is built for autonomous landing of a full-scale helicopter at unprepared sites. These researches mainly focus on the navigation system to derive a more accurate and stable relative position and orientation information between the UH and the landing site which is assumed to be stationary. In [3], tether is used to guide landing of UHs on a rocking ship deck, at the same time the tether tension is used to couple the translation of the UH to the rotation, two controllers are developed for far-away and near ship control, the main focus is on the stability of the proposed controller. In [4], a predictor is built up to estimate the movement of ship deck's altitude, and a feedback-feedforward controller is proposed based on the estimation of the wind disturbance to obtain more stable altitude control accuracy. These researches mainly focus on the stability of autonomous landing controller as the flight condition is different compared with the ground-based stationary landing.

As what has been reviewed in the pre-paragraph, currently the researches in autonomous landing mainly focus on navigation accuracy and controller stability, but seldom devote to the path planning for autonomous landing especially autonomous landing on a moving platform. While the landing on a moving platform can greatly expand the application field of UHs, for example, the autonomous landing on a moving ship can be of significant importance for ship-board applications since the main difference and challenge for UHs in ship-board applications compared with land-based applications is takeoff and landing. Compared with stationary landing, autonomous landing on a moving platform proposes more challenge on path planning because the strategy and method of path planning will directly decide the safety of autonomous landing.

Path planning for autonomous vehicles in three dimensional spaces to catch moving targets while avoiding obstacles in sensor-effective range is a challenging problem, especially when real-time is demanded in time-varying environment [5]. Mathematical programming methods treat the trajectory planning problem as a numerical optimization problem.

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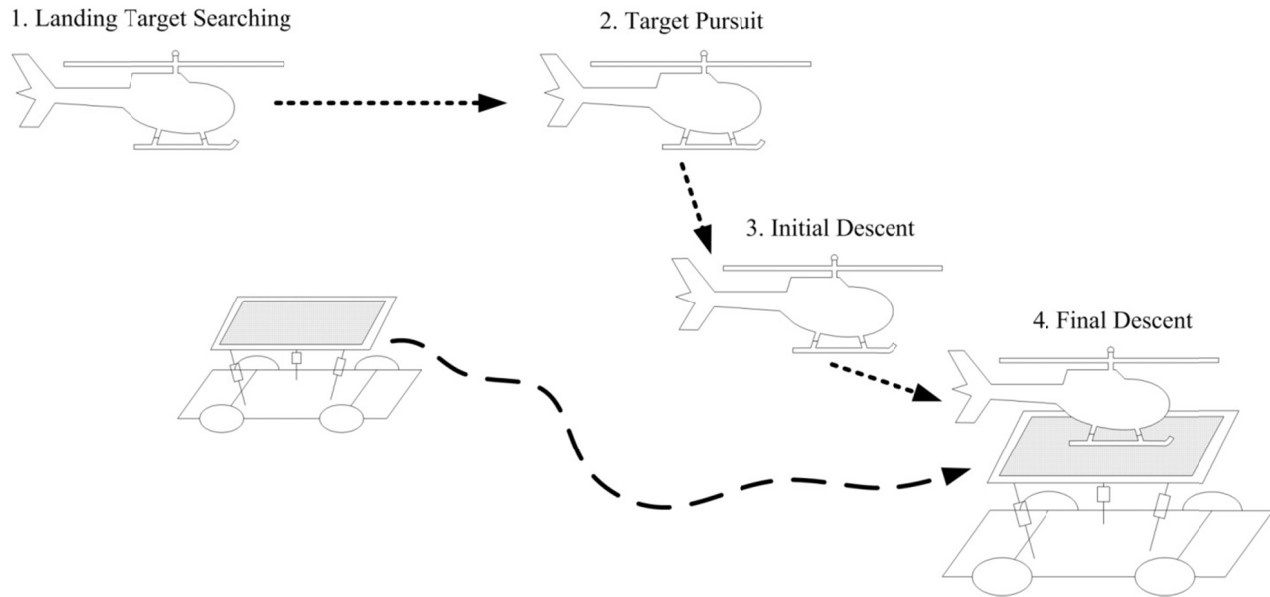


Figure 1 – Autonomous landing strategy

However, the cost functions typically have a number of local minima [10]; a proper selection of cost function is the most key factor for the implementation of mathematical programming methods. Linear programming (LP) is a general tool for optimization with the capability satisfying performance criterion and dynamic constraints. The path derived using either LP or mixed integer LP (MILP) ([7],[8]) is optimal with respect to an objective function while satisfying multiple constraints. However, it is difficult for MILP to be used as a real time path planner due to its computational complexity, and this is especially difficult when there are multiple moving obstacles with irregular contours [5]. In [6], the task of target-pursuit and obstacle-avoidance is modeled with linear constraints in relative coordination according to LP formulation, and two cost functions are integrated into the objective function of LP for obstacle-avoidance and target-pursuit respectively. Compared with ant colony optimization algorithm [9] and genetic algorithm [11], LP method has less parameter to tune and can achieve better performance in real-time application [6].

Tremendous progress has been made to increase the UHs' intelligence in Shenyang Institute of Automation Chinese Academy of Sciences before [14]–[19]. In this paper, LP is adopted for path planning of autonomous landing of a UH on a moving platform. First, the landing procedure is divided into four stages. Then, the linear constraints in each stage are established accordingly which include helicopter's flight envelope constraint and target kinematical constraint. Autonomous landing of an UH on a stationary platform, a moving platform and a moving ship have been realized respectively based on the proposed path planning method and the established hardware in the loop simulation system.

II. STATEMENT OF LANDING PROBLEM

Autonomous landing of an UH on a moving platform specified in this paper is defined as follow: As the platform T

moving on the ground with its lateral and longitudinal movement and attitudes vibration to simulate the movement of ship on the sea, the UH H tries to follow the horizontal movement of T at a safe altitude above the platform and at a proper time decrease its altitude to land on T with minimum attitude deviation, minimum position deviation and minimum relative velocity deviation in each axis to avoid strong shock and guarantee the safety of both UH and platform.

Generally, the autonomous landing procedure can be divided into four stages [2]:

1. Landing target searching

As the helicopter starts the autonomous landing procedure, landing target should be specified first. In this paper, we assume the target's information is pre-known and this stage can be ignored.

2. Target pursuit

The target is assumed to move on the ground with zero height; the initial altitude of UH would above the ground. Strategy for safe landing is to track the movement at a safe pursuit altitude and minimize the horizontal position deviation first. Pursuit at a safe altitude is requisite since flying at a low altitude will encounter more obstacles which would endanger the safety of UH.

3. Initial descent

If the UH has moved near the target with a proper horizontal position deviation, with the assumption that no obstacles exist above the landing zone, the UH will decrease its altitude to a safe landing altitude above the deck. This initial descent is to provide a period for landing deck verification and movement prediction.

4. Final descent

When the UH has finished the initial descent and safe landing has verified, final descent would execute to land on the deck at a minimum relative velocity in each axis and minimum position deviation in each axis.

III. LP FORMULATION

All the symbols and variables mentioned following are listed in **Table 1**. Assumptions for landing are list as follow [6]:

- The target's acceleration is assumed to be zero in the planning period. Since the planning period is short enough and the target's movement changes very slowly, this assumption can be satisfied generally. With this assumption, we have: $a_{HT} = a_H - a_T = a_H$.
- The target's velocity won't exceed the maximum velocity of helicopter; this will guarantee that the helicopter can catch up and land on the target finally.

Table 1 – Nomenclature

H, T	Helicopter, target
τ	Planning period
$\mathbf{v}_H$	Helicopter velocity in O_I
$\mathbf{v}_T$	Target velocity in O_I
$\mathbf{v}_{HT} = \mathbf{v}_H - \mathbf{v}_T$	Relative velocity
$\mathbf{p}_{HT} = (p_x, p_y, p_z)^T$	Relative position
$W_{HT} = \mathbf{v}_{HT}^T \mathbf{p}_{HT}$	Temporal variable
$\mathbf{a}_H = (a_x, a_y, a_z)^T$	Helicopter acceleration
$\mathbf{a}_{HT}$	Relative acceleration
γ_{HTI}	Angle between horizontal relative velocity and horizontal position
q_1, q_2	Auxiliary variable
V_H, V_T, V_{HT}, P_{HT}	Magnitude of corresponding vector
$\mathbf{v}_{HTI}, \mathbf{p}_{HTI}, W_{HTI}, \mathbf{a}_I$	x-y component of corresponding vector

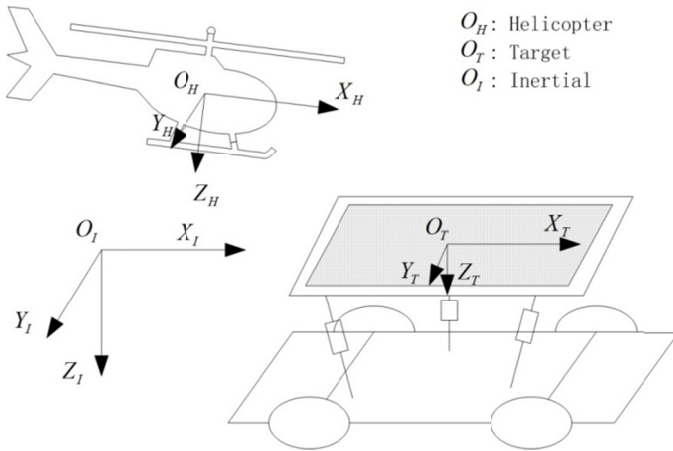


Figure 2 – Coordinates definition

The coordinates used in this paper are defined as shown in **Figure 2**, with O_H the helicopter body-fix reference frame, O_T the moving target body-fix reference frame, O_I the inertial reference frame.

LP formulations for target pursuit are separated into horizontal position pursuit, yaw pursuit and altitude position pursuit respectively. In different land stages, different planning strategies will be employed based on the combination of these formulations.

A. Horizontal position pursuit

With the horizontal relative velocity $\mathbf{v}_{HTI}$ and its orthogonal component V_{CI} and V_{TI} depicted in **Figure 3**, the policy for the optimal velocity in horizontal is defined as following:

$$\min : V_{TI} = \|\mathbf{v}_{HTI}\| \sin \gamma_{HTI} \quad (1)$$

$$\max : V_{CI} = \|\mathbf{v}_{HTI}\| \cos \gamma_{HTI} \quad (2)$$

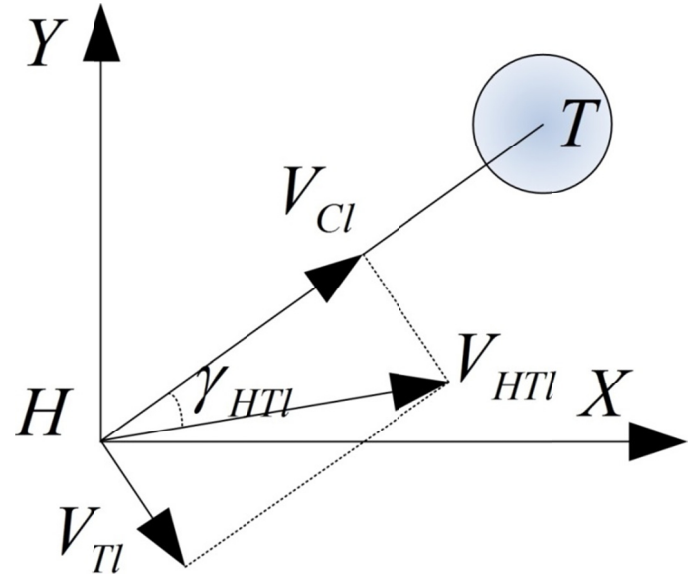


Figure 3 – Horizontal relative velocity and orthogonal components V_{CI} and V_{TI}

Considering the dynamic constraints of the UH, we have following constraints:

1) Velocity constraint

Since the projecting plane of the lateral airframe is much wider compared with the longitudinal airframe, wind resistance exerts on lateral movement would be bigger which results in a less maximum lateral velocity. The maximum velocity is different in lateral and longitudinal axis, generally used simplification such as a unified square or circle can't satisfy the requirement, here we assume the helicopter's velocity satisfy the constraint as an ellipse:

$$\frac{v_{Hx}^2}{V_{Mx}^2} + \frac{v_{Hy}^2}{V_{My}^2} \leq 1 \quad (3)$$

where v_{Hx} and v_{Hy} are the longitudinal and lateral velocity of UH respectively, V_{Mx} and V_{My} are the maximum velocity in

longitudinal and lateral axis respectively. Generally, V_{My} would be half of V_{Mx} .

Multi-planes are used to approximate the ellipse constraints of velocity as shown in (3) to satisfy the linear constraint requirement of LP.

$$\frac{\sin \varphi_m v_{Hx}}{V_{Mx}} + \frac{\cos \varphi_m v_{Hy}}{V_{My}} \leq 1 \quad (4)$$

where $\varphi_m = 2m\pi / M$, $m = 1, \dots, M$

2) Acceleration constraint

The feasible region of helicopter's acceleration is as follow. Like (4), multi-planes [6] are used to approximate the constraints of acceleration.

$$a_x^2 + a_y^2 \leq a_{\max}^2 \quad (5)$$

$$\sin \theta_m a_x + \cos \theta_m a_y \leq a_{\max} \quad (6)$$

where $\theta_m = 2m\pi / M$, $m = 1, \dots, M$.

According to [6], we have the optimization rule as following:

$$\begin{cases} J = 0.5q_1 + 0.5q_2 \\ -\tau \left[\left(\mathbf{v}_{HTI} - \frac{W_{HTI}}{\mathbf{p}_{HTI}^2} \right)^T \mathbf{a} \right] \leq \left(v_{HTI}^2 - \frac{W_{HTI}^2}{P_{HTI}^2} \right) \\ \tau \left[\left(\mathbf{v}_{HTI} - \frac{W_{HTI}}{\mathbf{p}_{HTI}^2} \right)^T \mathbf{a} \right] - q_1 \sqrt{\left(v_{HTI}^2 - \frac{W_{HTI}^2}{P_{HTI}^2} \right)} \leq - \left(v_{HTI}^2 - \frac{W_{HTI}^2}{P_{HTI}^2} \right) \\ -\tau (\mathbf{p}_{HTI}^T \mathbf{a}) - P_{HTI} q_2 \leq W_{HTI} \\ 0 \leq q_1 \leq 2V_{\max} \\ -V_{\max} - V_T \leq q_2 \leq V_{\max} + V_T \\ \sin \theta_m a_x + \cos \theta_m a_y \leq a_{\max} \\ \frac{\sin \varphi_m v_{Hx}}{V_{Mx}} + \frac{\cos \varphi_m v_{Hy}}{V_{My}} \leq 1 \end{cases} \quad (7)$$

B. Yaw pursuit

As what has been stated in velocity constraint, lateral maximum velocity and longitudinal velocity is different. Then the optimal yaw is to align the helicopter with the $\mathbf{P}_{HT}$ under the constraint of the maximum yaw rate limitation.

$$\begin{cases} J = \min |\psi - \angle \mathbf{P}_{HT}| \\ |r| \leq r_{\max} \end{cases} \quad (8)$$

where ψ is the yaw of helicopter, $r_{\max}$ is the maximum yaw rate of helicopter.

Actually, yaw pursuit is only required when the helicopter is far away from the target. As the helicopter near the target, velocity in any axis can track the movement of target and yaw pursuit is of no sense anymore.

C. Altitude pursuit

Altitude pursuit has its special requirement: compared with the horizontal pursuit, relative vertical velocity must be minimized to avoid the landing accident. A balance should be made between the relative altitude deviation and the relative vertical velocity. Here target is assumed to be on the ground without vertical movement, this will simplify the problem, and we have the LP formulation as following:

$$\begin{cases} J = \min |P_z| + k_v |v_z| \\ |v_z| \leq v_{z\max} \\ |a_z| \leq a_{z\max} \end{cases} \quad (9)$$

where k_v is the weight factor which will make a balance between the altitude bias and relative touching velocity, and is selected in accordance with the maximum decent velocity defined in autonomous landing.

IV. SIMULATION AND RESULT

A hardware-in-the-loop (HIL) simulation and test platform has been developed for algorithms simulation and validation [12]. The simulation system includes a 3D flight and scenery simulator, a flight control system, a ground control station, and a RC pilot controller. Based on a semi-decoupled flight dynamic model, which is acquired from a frequency domain system identification method using real flight hovering data, an autonomous PID controller is implemented and verified in both simulation and real flight tests. The simulation system is shown in **Figure 4**. An extra computer is utilized to simulate movement of the moving target and send target's information to the flight controller for path planning. LP solver for path planning is realized on a computer and the path planning result is then sends to the flight controller. The architecture of the overall simulation system is as shown in **Figure 5**.

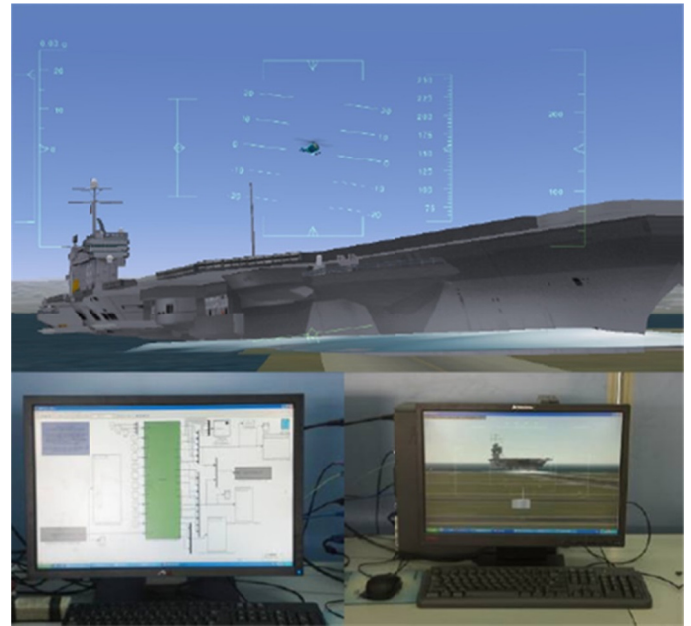


Figure 4 – Simulation system

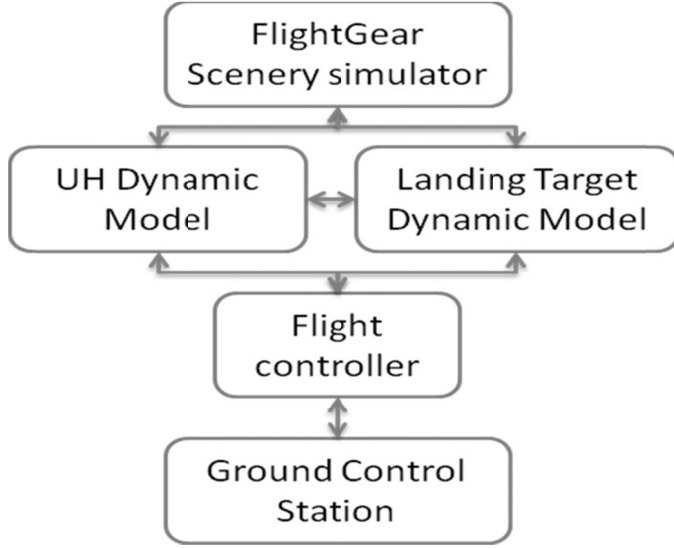


Figure 5 – Simulation system architecture

Three simulations are conducted: first we demonstrate the autonomous landing on a stationary platform, and then landing on a moving platform is further demonstrated, autonomous landing a moving ship is conducted finally to validate the overall system and the effectiveness of the proposed algorithms.

The UH dynamic constraints and parameters for simulation are listed in Table 2. These constraints and parameters are the real value specified by the UH we developed as Servoheli-40.

Table 2 – Dynamic constraints and parameters

V_{Mx}	V_{My}	a_{max}	τ	v_{zMax}	a_{zMax}
20 m/s	10 m/s	3 m/s ²	0.5 s	3 m/s	1 m/s ²

A. Landing on a stationary platform

In this simulation, the landing target is assumed to be at a fix point without movement; the helicopter hovering at an initial position is expected to move to and land on the target. States for simulation are listed in Table 3.

Table 3 – States for Stationary landing

P_T	P_H	V_H	V_T	a_H	φ
(300, 250, 0)	(0, 0, -50)	(0, 0, 0)	(0, 0, 0)	(0, 0, 0)	0

Figure 6 shows the path planning result for the stationary landing. A comparison is made between the fix yaw pursuit and the pursuit with yaw dynamically aligned with the target. As the Figure 6 showing, they have almost the same flying pursuit trace. The black arrow in the figure is the yaw of the UH, as we can see, the yaw will finally aligned with the target. But as shown in Figure 7, the velocity in x-axis is different; a maximum pursuit velocity can be reached which decreases the landing period from 1180 steps to 799 steps. This result demonstrates the validity of the necessity of dynamic yaw alignment and the effectivity of the whole landing strategy.

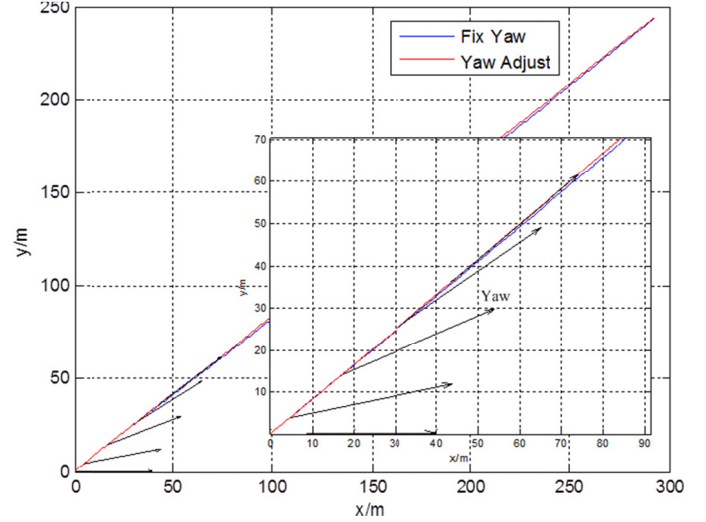


Figure 6 – Stationary landing: flying trace at vertical view, black arrows represent yaw of the UH

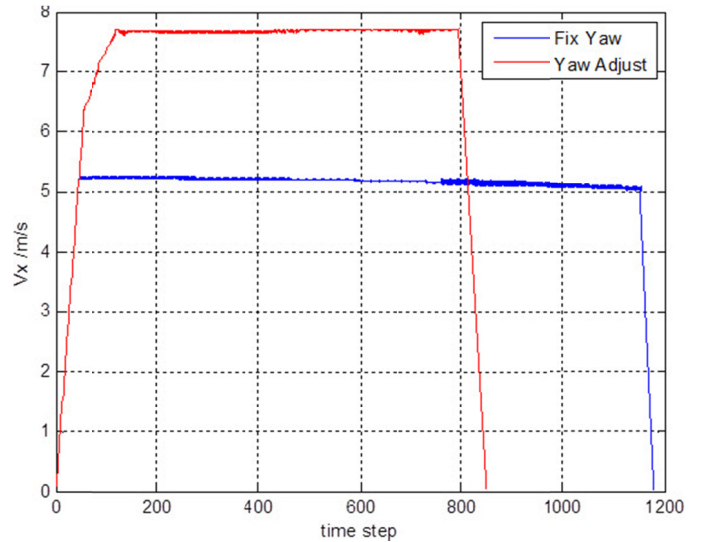


Figure 7 – Stationary landing: flying velocity in x-axis

B. Landing on a moving platform

In this simulation, the target is moving at a speed of (3,5,0) first and then the speed changes to (-5,-1,0) at time step 300, States for simulation are listed in Table 4.

Table 4 – States for Moving Platform Landing

P_T	P_H	V_H	V_T	a_H	φ
(300, 250, 0)	(0, 0, -50)	(0, 0, 0)	(3, 5, 0)	(0, 0, 0)	0
			(-5, -1, 0) as k>300		

The pursuit trace is shown in Figure 8, as we can see, even with a sudden velocity change, the helicopter can finish the pursuit and landing. Figure 9 is the altitude deviation and vertical velocity, this implies that the helicopter can landing on the target with almost zero relative vertical velocity to minimize the shock of landing.

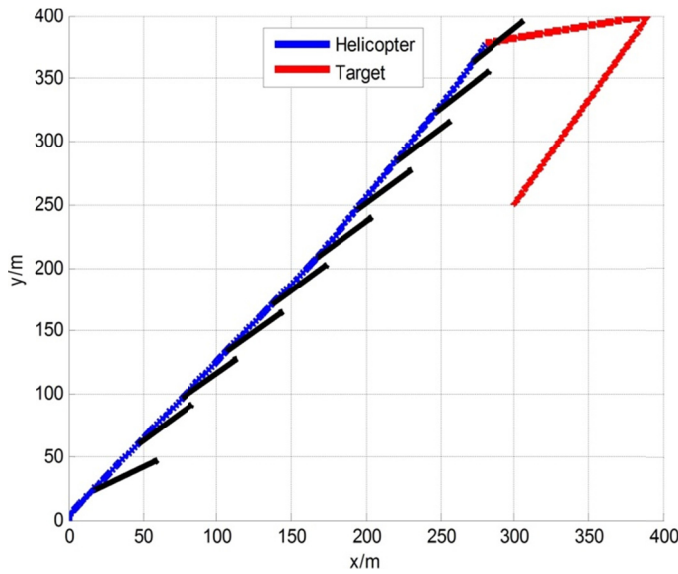


Figure 8 – Landing on a moving platform: flying trace vertical view, black arrows represent yaw of the UH

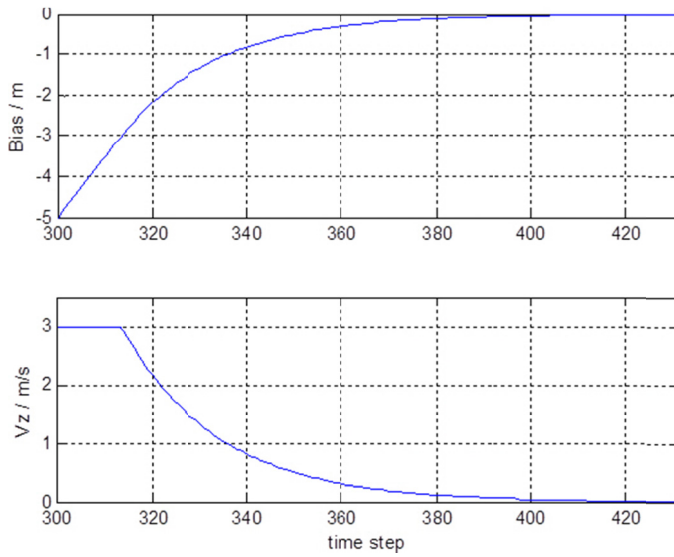


Figure 9 – Landing on a moving platform: altitude deviation and vertical velocity

C. Landing on a moving ship

To validate the proposed algorithm and the simulation system, here a simulation of an UH autonomously landing on a moving ship is conducted. In the simulation, the UH is supposed to track a moving ship and land on it properly.

A simplified ship dynamic model is used to simulate the movement of a real ship; the model is list as following:

$$\left. \begin{aligned} \dot{x} &= u \cos \varphi - v \sin \varphi & \dot{u} &= \frac{m_{22}}{m_{11}} vr - \frac{d_{11}}{m_{11}} u + \frac{1}{m_{11}} \tau_u \\ \dot{y} &= u \sin \varphi + v \cos \varphi & \dot{v} &= \frac{m_{11}}{m_{22}} ur - \frac{d_{22}}{m_{22}} v \\ \dot{\varphi} &= r & \dot{r} &= \frac{m_{11} - m_{22}}{m_{33}} uv - \frac{d_{33}}{m_{33}} r + \frac{1}{m_{33}} \tau_r \end{aligned} \right\} (10)$$

where x and y are the position in north and east coordination respectively, φ and r are the orientation and yaw rate, u and v are the velocity in body axis, τ_u and τ_r are the control input. The parameters of ship are listed as following:

$$\begin{aligned} m_{11} &= 143kg, m_{22} = 200kg, m_{33} = 270kg \\ d_{11} &= 70kg/s, d_{22} = 100kg/s, d_{33} = 50kg/s \end{aligned}$$

The simulation result is shown in Figure 10 and Figure 11. As shown in Figure 10, as the UH start landing procedure, it will follow the predefined procedure: target pursuit, initial descent, final descent, landing on the ship. The UH can autonomous track and land on the ship with the predefined strategy.

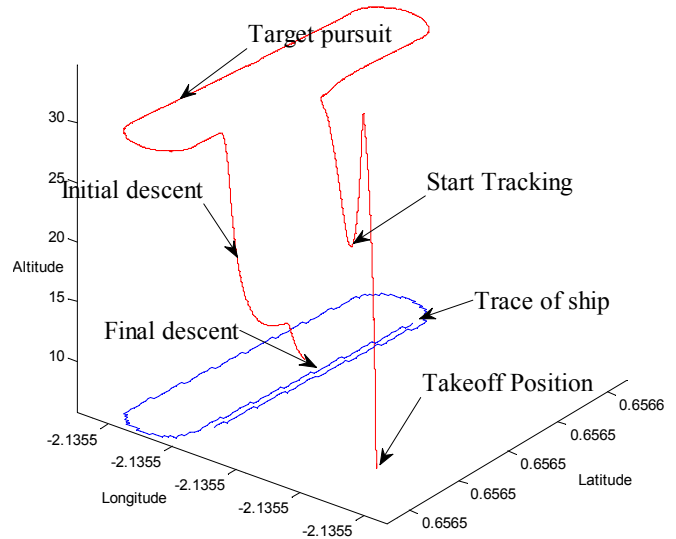


Figure 10 – Landing on a moving ship: trace of the UH and the ship

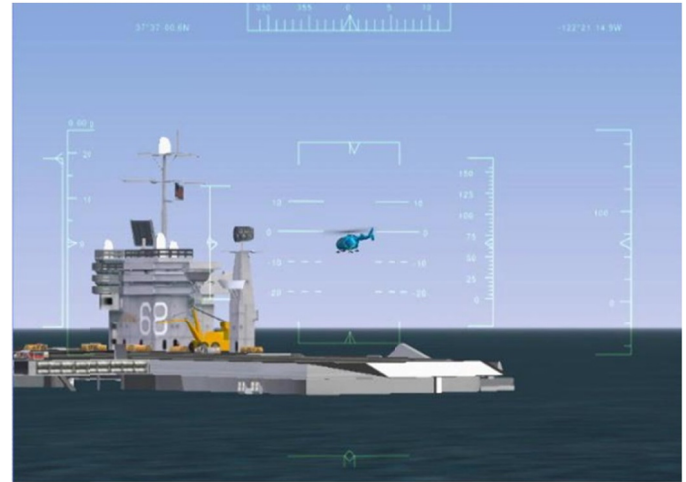


Figure 11 – Screen shot of landing on a moving ship

V. CONCLUSION

With the proposed strategy for autonomous landing of an unmanned helicopter on a moving platform, this paper established a path planning algorithm based on LP method. Incorporating the UH dynamic constraints and flight envelop constraints, LP formulations for horizontal pursuit, yaw pursuit

and vertical pursuit have been established respectively. A hardware-in-the-loop simulation and test platform has been established based on Matlab and FlightGear for algorithms validation purpose, further investigation on flight controller design and path planning can also be conducted on this platform. Autonomous landing of an UH on a stationary platform, a moving platform and a moving ship have been realized based on the proposed path planning algorithms and the established simulation platform. The simulation results demonstrate that with the proposed algorithm the UH can successfully pursue and land on a moving target with a safe landing strategy and safe relative touching velocity.

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