

# IEEE CGNCC 2014

August 8-10, 2014, Yantai, China

## Program Digest



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| Zhilin Liao   | China Helicopter Research and Development Institute                                      | National Key Laboratory of Science and Technology Aviation Industry Corporation of China                      |
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| Xianglun Zhang  | Xi'an Flight Automatic Control Research Institute  | Qing Lin Beihang Univ.  |
|   | Science and Technology on Aircraft Control Laboratory                                    | Dongze Huang Beihang Univ.  |
| Jun Che   | Xi'an Flight Automatic Control Research Institute  | Jinpeng Yang Beihang Univ.  |
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# Mission-Oriented Control Scheme for Autonomous/Semi-Autonomous UCAV

Xieyu Xu, Lingyu Yang, Xiao Hu, and Jing Zhang

**Abstract**—This paper discusses the scheme and design method for UCAV autonomous/semi-autonomous control system. According to the investigation of the traditional tactical flight maneuvers and the existing air combat simulators, a mission-oriented control scheme is proposed to fulfill the autonomous/semi-autonomous requirements. A library including 9 maneuvers is designed by which complex tasks could be formed. And base on the flight mechanics, a control structure of line motion-angular motion is proposed to simplify the implementation of flight maneuvers. Finally, the proposed method is validated through simulations of a nonlinear six degrees of freedom UAV model.

## I. INTRODUCTION

The Uninhabited Combat Aerial Vehicles (UCAV) has unique advantages over regular manned aerial vehicle, such as lower cost and higher maneuverability, which has become a research hotspot all around the world<sup>[1,2,3]</sup>. Currently, UCAV such as Dassault nEUROn, Boeing X-45 from and Northrop Grumman X-47, has been put into the flight test and verification. United States Department of Defense predicts that UCAV will implement autonomous air combat tasks around the year 2025.

The challenge of the UCAV replacing the manned vehicle is the autonomous design. Researches have been carried over relevant fields, resulting in a variety of layered hierarchical control structure and algorithms, such as path planning, target assignment, automatic formation and cooperative combat, etc., some of which have been validated by flight test. But most of the existing research typically aims at a simple specific task or a specific target in a specific situation. For complicated tactical situations such as autonomous air combat or manned/unmanned aircraft cooperative combat, current study is not sufficient.

Considering the mission-oriented design philosophy for UCAV control system, a control structure for UCAV autonomous/semi-autonomous air combat is proposed in this paper. Through classifying, summarizing and concluding the existing manned air combat techniques, a library of combat

maneuvers dedicated for UCAV is developed. The library is expected to cover as many air combat requirements as possible, to reduce the work load of UCAV operators, and to contribute to autonomous/semi-autonomous algorithms, such as intelligent decision machines.

## II. AUTONOMOUS/SEMI-AUTONOMOUS CONTROL SCHEME BASED ON MANEUVER LIBRARY

A fighter pilot needs to consider many factors synthetically during air combat, such as the tactical situation, vehicle performance, sensor characteristics and weapon launch conditions, which make the analysis of air combat process very complex. As a result, there are vast difficulties taking all constraints and detailed combat process into consideration, which makes it hard to analysis and design autonomous control algorithms.

The general control structure of autonomous UCAV is a layered hierarchical structure. Based on real-time combat situation, a decision unit at the top of the layers seeks the best solution from a collection of predefined battle tactics. To the semi-autonomous UCAV guided by a ground station or a manned lead aircraft, the appropriate command should be a discrete command sequence as well, instead of continuous real-time stick signals.

In the aspect of common air combat processes, although the process varies in different ways, there should be fixed models in the processes, which have already been summarized as air combat techniques in air combat history, such as basic flight maneuvers, etc. With those combat techniques, a complicated combat process could be decomposed into several simple flight processes and their concatenations, which not only serves for pilot assessment, but also facilitates theoretical analysis.

Based on above discussion, continuous air combat process can be decomposed into several successive basic maneuvers, forming the maneuver library. Then the whole air combat process can be studied separately via its composing maneuvers. With this analysis method, an autonomous/semi-autonomous UCAV control structure can be proposed. An operator or autonomous decision machine percepts current combat situation, selects the most suitable maneuver and executes the maneuver by underlying controllers. Through the repetition of this perception, selection and execution procedure, a certain level of autonomous air combat capability of UCAV can be achieved. This design method has not been put into experiments, but has already become an important air combat simulation and analysis tool<sup>[6,7,8]</sup>.

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Combining the air combat experience and the existing designs of air combat simulators, 2 assumptions about the actual air combat process are made as follows:

- (1) A complicated air combat process could be decomposed into several successive maneuvers and their concatenations;
- (2) Every maneuver should possess a clear tactical significance.

A maneuver library can be formed by summarizing and synthesizing these combat maneuvers. In an actual air combat task, operator or autonomous decision machine perceives the combat situation, selects the most suitable maneuver from the library, and executes the maneuver via underlying controllers, just like the procedure mentioned above. The whole control scheme is shown as Fig. 1.

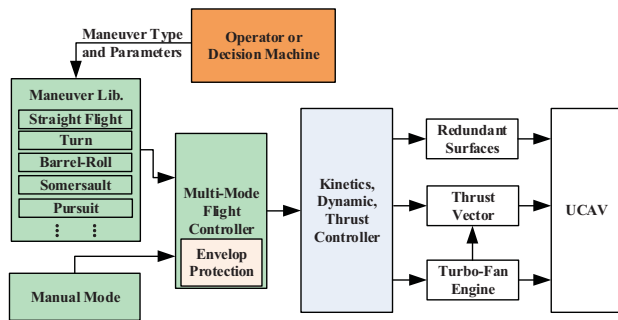


Figure 1. Mission-oriented control scheme for autonomous/semi-autonomous UCAV.

The rationality of the design method in this paper can be verified through typical flight courses. Such as the crossing target acquisition and tracking course mentioned in reference [9] for high-alpha handling quality flight test, requires that candidate vehicle points to target vehicle as soon as possible and keeps a pointing accuracy of about  $1.6^\circ$  for 2.5 seconds. At the beginning of the course, two vehicles keep 500ft away from each other in height without lateral displacement. During the course, the target keeps a steady 5g and turn towards candidate without loss of height and velocity. The performance parameters of candidate vehicle are measured by target acquisition time and sustained tracking time. Considering the large aspect angle and the small displacement in the initial condition, a high-alpha pointing is required to directly point to the target, which is unpractical due to great loss of speed and sustainable pointing ability. It is expected that the velocity vector should aim at target approximately at first and point precisely to target at last. Thus the whole process can be decomposed into four phases as follows:

- (1) Perform a high load and turn towards the target until it appears on radar screen;
- (2) Lead pursuit the target, until the pointing error is within the capability of the attitude pointing;
- (3) Point to target precisely, maintaining the tracking time as required;
- (4) Stop pointing and wait for next command, or repeat above procedures to another target.

It's easy to see that the crossing target acquisition and tracking course can be decomposed into 4 maneuvers including high load turning, lead pursuit, attitude pointing and exiting, and their concatenating logic. If these maneuvers could be implemented in the maneuver library, the course can be completed through proper selection of maneuvers and switch between them.

For some other common air combat maneuvers, they could be roughly decomposed and analyzed using the procedures above, shown in table 1.

TABLE I. DECOMPOSITION OF COMMON COMBAT MANEUVERS

| Combat Maneuvers | Analysis   |
|------------------|--|
| Intercept        | Conduct pure guidance to target until weapon launch condition satisfied.                         |
| Rounding Attack  | Approach target with distance constraints until entering its rear sphere for tactical advantage. |
|                  | Turn to target.  |
| High Yo-Yo       | Lead pursuit until weapon launch condition satisfied.  |
|                  | Pull up until target approaching speed is reduced sufficiently.                                  |
| Herbst           | Lead/Lag/Pure pursuit, until weapon launch condition satisfied.                                  |
|                  | High alpha maneuver for deceleration.  |
|                  | Roll around speed vector as desired.   |
|                  | Accelerate to regain speed.  |

The above cases prove that selection and concatenation of maneuvers can achieve common air combat maneuvers. The structure of maneuver library can satisfy the requirements of common air combat tasks.

### III. DESIGN METHOD OF MANEUVER LIBRARY

Currently, maneuvers are often discussed together with flight simulators and autonomous decision machines.

Reference [10] divides maneuver designs into 2 types, typical tactical maneuvers and basic manipulative maneuvers. Reference [6] provides 24 typical tactical maneuvers, based on which a simulation program for air combat of two vehicles is designed. Each maneuver in the reference can define detailed kinetics parameters such as load and roll angle, but the maneuver itself is not described quantitatively. Reference [7] designs 7 maneuvers, including maximum load factor turning left and right, maximum longitudinal acceleration, steady flight, maximum longitudinal deceleration, maximum load factor pull up, maximum load factor push over. In each control cycle, one of those maneuvers is chosen to be executed. It's obvious that this design is definitely rough and the vehicle is always working to its limit. In addition, it couldn't reflect the actual air combat conditions and task requirements.

In reference [11], an autonomous control scheme and decision-making system of UCAV is provided. The design of UCAV tasks contains parking, taxiing, taking-off, climbing, travelling, target reconnaissance, target attacking, circling, descending and landing. The design emphasizes normal flight processes like taking off and landing, and ground movements like parking and taxiing. For target reconnaissance, the reference design automatically generates a rectangle-shaped or diamond-spiral-shaped route and controls the UCAV flying along the generated route. For target attacking, the design only declares that different trajectories are made for different

ammunition. In summarize, a detailed design for normal cruise operations is well studied in the paper, but the design for specific tactical missions remains rough.

Similar research has also been conducted in MIT [4]. Designed missions include flying to the specific waypoint, loitering, searching, classifying target, attacking targets, battle damage assessment and returning-to-base, in total of 7 categories. But the paper doesn't explain how to implement them in detail. As the research is focused on a full set of systems such as natural language processing, automatic path planning and so on, it makes little sense to maneuver design method, though actual flight test was carried out in 2004.

Reference [12] synthesizes common air combat tactical maneuvers, introduces the concept of maneuver parameters and designs 10 maneuvers in detail, including straight flight, turning, rolling, barrel-roll, inverted half somersault, half somersault, pursuit, scissoring, high yo-yo, low yo-yo. But the classification of the maneuvers is still rough in some ways. For example, the rolling and the barrel-roll maneuver share the same design objectives that reducing the velocity and confusing maneuvering plane, but only differ in vertical load magnitude. Half somersault and inverted half somersault are only different in load direction. Scissoring, high yo-yo and low yo-yo are the combination of above maneuvers, such as high yo-yo can be implemented through a tilted half somersault and a lead pursuit. They should be divided into detailed maneuvers and reconstructed on the judge of a decision-making machine or UAV operator.

But reference [12] presents a design philosophy that designing the maneuver parameters besides the types of maneuvers. We could change the maneuvers and even their tactical sense through adjusting parameters. In other words, parameter adjustment expands the capability of a certain maneuver design and reduces maneuver types on the premise of keeping combat significance.

It can be seen from the above analysis that the design of the maneuvers should satisfy the following conditions: The design of the maneuvers should be abstract enough, breaking away from traditional operating actions such as pulling stick, and reflecting the tactical sense of the maneuvers as much as possible; the design of the maneuvers should not be too much abstract, otherwise it might diminish the solution space, loss the optimality of the solution and reduce the performance of completing tasks.

Combining with former designs, the maneuver library designed in this paper is shown as table 2.

This design covers most maneuvers mentioned above, and complies with intuition. The abstraction level of the maneuvers is relatively low. Algorithm such as detailed path planning process is not considered here. The design does not list specific tasks (target attacking, for example) as maneuvers separately. Considering the varieties of ammunition characteristics and target types, a uniform maneuver design might reduce overall performance. Detailed mission strategy and flight path can be decided by an operator or generated by decision algorithms.

Common combat maneuvers can be implemented through the design in this paper. Such as lead pursuit and lag pursuit mentioned above, can be implemented by adjusting the leading angle of the pursuit maneuver. High yo-yo can be generated by combining somersault maneuver and pursuit maneuver. Interception and collision problems, which are not mentioned in above designs, can be implemented by approaching maneuvers. Furthermore, with the evolution of UCAV performance and air combat mode, new maneuvers can be added into library to extend UCAV mission capability, such as high-alpha post-stall maneuvers.

TABLE II. DESIGN OF MANEUVER LIBRARY

| No. | Name            | Param. 1                | Param. 2                          | Param. 3     | Tactical Sense  |
|-----|-----------------|-------------------------|-----------------------------------|--------------|---|
| 1   | Straight flight | Heading angle           | Path angle                        | Acceleration | Change velocity and position. Join different maneuvers. |
| 2   | Turn            | Heading angular speed   | Path angle                        | Acceleration | Change course horizontally.                             |
| 3   | Barrel-roll     | Intense ratio           |                                   |              | Threat avoidance  |
| 4   | Somersault      | Normal acceleration     | Incline angle of somersault plane |              | Change course vertically                                |
| 5   | Cruise          | Course angle constraint | Distance constraint to the course | Velocity     | Trajectory following                                    |
| 6   | Formation       | Relative direction      | Distance to target                |              | Formation flight  |
| 7   | Pursuit         | Lead angle              | Velocity                          |              | Pursuit target  |
| 8   | Pointing        |                         |                                   |              | Aim at target for weapon launch, etc.                   |
| 9   | Approach        | Lead angle              | Distance constraint to target     | Velocity     | Approach target for interception, etc.                  |

The command the UCAV actual gets might be coarse in semi-autonomous missions. For example, straight flight maneuver requires exact course angle and acceleration parameters, but actual command given might be imprecise like "decelerate slowly at one o'clock", which could be interpreted by a translator to detailed quantified commands. Maneuver command might be too much abstract, for example, the operator requests executing target reconnaissance task, which is not a maneuver listed in library. An appropriate flight trajectory needs to be generated by a path planning algorithm, followed with cruise maneuver which makes UCAV follow

the generated path, thus achieving the requirement of the reconnaissance mission. In general, although the maneuver library designed in this paper doesn't directly contain missions such as avoiding threats, area reconnaissance, target attacking and so on, these tasks can be indirectly accomplished through the maneuver library with appropriate path planning algorithm and autonomous decision machine. In this way, the maneuver library designed in this paper can satisfy the requirement of different missions.

#### IV. STRUCTURE OF THE MANEUVER CONTROLLER

When the maneuver library is confirmed in detail, underlying maneuver controller should be designed to execute different maneuvers. It is possible that the maneuvers designed in this paper might not be comprehensive and the maneuver library adopted in real systems might be abundant. It's necessary to design an appropriate structure of the control law to simplify the design process of maneuver controllers.

In the view of flight mechanics, the forces a plane suffers include aerodynamic forces, thrust and gravity. Considering the constant magnitude of gravity, the fixed direction relations between thrust, gravity and aircraft attitude, and that thrust vector is only used to change aircraft attitude, the only force that could be controlled both in magnitude and direction is the aerodynamic forces, while the force can be controlled in magnitude solely is thrust. The aerodynamic forces relate directly to the wind angles, which are functions of both directions of velocity and aircraft attitude. Thus we could control the forces of an aircraft by controlling the wind angles and thrust. The design of control structure is shown as Fig. 2.

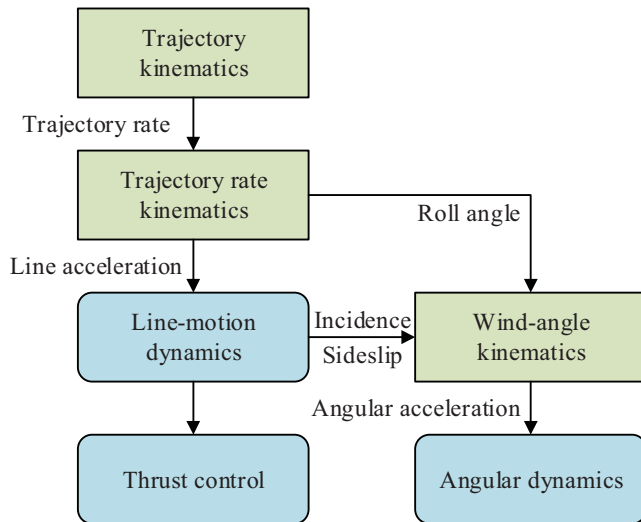


Figure 2. Structure of maneuver controller.

Considering the overall fighter performance such as stealth, flight performance, viability, etc., stealth layout and multiple control surfaces configuration are a design trend for future fighters. Multiple control surfaces contributes to the redundant control ability and might lead to the coupling of longitudinal and lateral effectiveness of different surfaces, which can be solved with control allocation algorithms, corresponding to the angular acceleration dynamic part of the control structure in this paper. Because of the kinetics constraints between the wind angles, velocity direction as well as aircraft attitude, the control of wind angle is equivalent to arranging the transition process of the angular motion, which is designed in the wind angle kinematic part of the control structure. Similarly, the process generating desired wind angle command from expected acceleration commands belongs to the category of linear acceleration dynamics. There also exists definite kinetics constraints between position, velocity and acceleration, the control of which is equivalent to arranging the transition process of the linear motion, which falls in the category of linear dynamics.

Corresponding to flight mechanics, different maneuvers propose different control objectives at different motion levels. For example, straight line maneuver needs to maintain flight course, formation flight needs to maintain the distance between two aircrafts, pointing maneuver needs to control aircraft attitude, etc. It's easy to see that the 9 maneuvers designed in this paper can be simply classified into 4 categories according to the control structure discussed above, shown as table 3.

TABLE III. CLASSIFICATIONS OF MANEUVERS

| No. | Name            | Category | Remark                                      |
|-----|-----------------|----------|---|
| 8   | Pointing        | I        | Control of attitude                         |
| 3   | Barrel-roll     | II       | Control of roll angle and normal load       |
| 4   | Somersault      |          |   |
| 1   | Straight flight | III      | Control of magnitude and direction of speed |
| 2   | Turn            |          |   |
| 5   | Cruise          | IV       | Control of relative position                |
| 6   | Formation       |          |   |
| 7   | Pursuit         |          |   |
| 9   | Approach        |          |   |

Introducing different control commands in different phases, various control requirements can be fulfilled. For example, pointing maneuver controller can generate wind angle command directly from target information, formation maneuver can directly generate expected velocity and relative position commands, etc. Different control commands should be generated according to different maneuvers and output to appropriate levels, then different combat maneuvers are implemented.

#### V. SIMULATION AND VERIFICATION

##### A. Verification of Maneuver Control Structure

Two typical maneuvers, barrel-roll and pointing, are verified in this section.

Barrel-roll maneuver requires that the aircraft rolls and pitches simultaneously, which vastly reduces aircraft velocity and constantly changes maneuver plane, preventing locked by enemy aircrafts. The intense ratio parameter  $p$  is the only parameter designed for this maneuver, whose value varies between -1 and +1. The detailed kinematic commands generated from  $p$  are shown as follows:

$$\begin{aligned} a_{x,c}^w &= k_x |p| \\ a_{y,c}^w &= k_y |p|. \\ \omega_{x,c} &= k_\omega p \end{aligned} \quad (1)$$

Wherein,  $a_{x,c}^w$ ,  $a_{y,c}^w$  are accelerations in the wind coordinate frame, determining flight trajectory, and  $\omega_{x,c}$  is the rolling angular velocity in body coordinate frame and reflects the direction of the lift force. The meaning of the commands is to generate appropriate deceleration, vertical load and rolling velocity base on parameter  $p$ . The simulation results under the condition " $p = 1$ " is shown as Fig. 3.

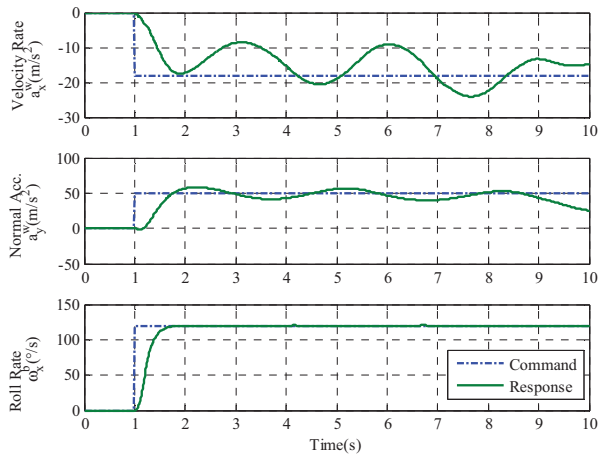


Figure 3. Simulation results of barrel-roll maneuver.

Simulation results show that the designed maneuver control structure cannot track reference input accurately enough due to the violent motion of maneuvers. But it can fulfill the task requirements like reducing the velocity and changing the maneuver plane. Thus it can be concluded that the proposed design of control structure is successful.

The pointing maneuver requires that the aircraft points its nose to the target as quickly as possible. A set of Sharkenhausen [9] test maneuver is carried over pointing maneuver, the simulation results of which are shown as Fig. 4 and Fig. 5.

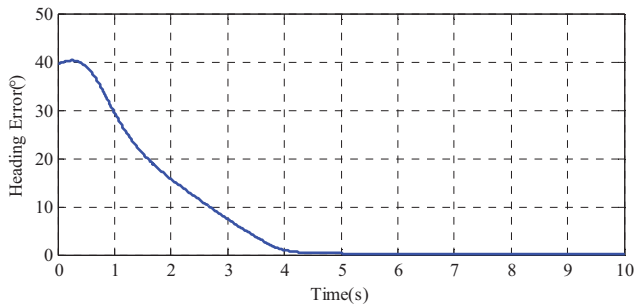


Figure 4. Heading error in Sharkenhausen maneuver simulation.

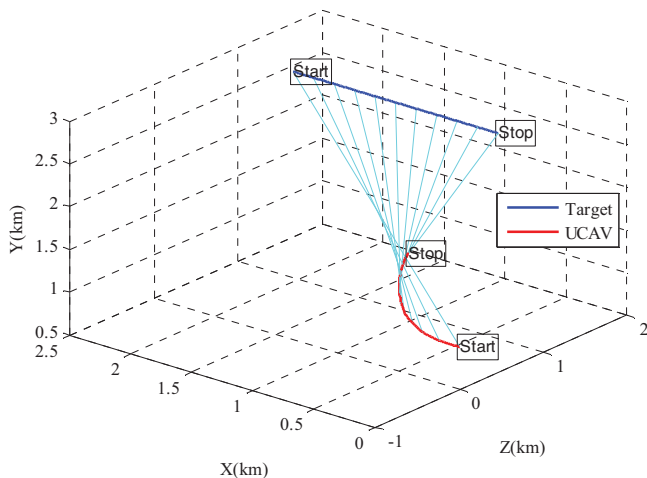


Figure 5. Space trajectory of Sharkenhausen maneuver simulation.

It's easy to see that the UCAV can point to the target quickly and maintain pointing process accurately for a while. It can also be concluded that the design of the control law is successful.

### B. Manned/UCAV Cooperative Combat Task Case

1) *Initial state*: A squadron with a manned aircraft and a UCAV tries to intercept a target aircraft, which is a manned aircraft, heading face to face.

2) *Combat task*: Assumes that the manned aircraft and the UCAV execute the attacking mission together. Considering that the UCAV is harder to be detected than manned aircraft due to smaller RCS, it is expected that the UCAV could round to the rear of the target and attack stealthily. The detailed phases of the intercept task are shown as table 4.

TABLE IV. PHASES OF COOPERATE COMBAT TASK

| No. | Phase     | Remark   |
|-----|-----------|--|
| 1   | Formation | UCAV and manned aircraft fly to target area in a designed formation.                 |
| 2   | Approach  | UCAV leaves formation and tries to approach target with lateral distance constraint. |
| 3   | Rounding  | UCAV tries to increase aspect angle while maintain the distance to target.           |
| 4   | Attack    | UCAV and manned aircraft attack to target simultaneous.                              |

According to the maneuver library designed in this paper, the detailed commands that the UCAV might receive are shown as table 5.

TABLE V. MANEUVERS OF COOPERATE COMBAT TASK

| No. | Time(s) | Maneuver  |
|-----|---------|---|
| 1   | 0       | Formation with manned aircraft.                                 |
| 2   | 5       | Cruise with distance constraints on expected target trajectory. |
| 3   | 23.5    | Lead angle pursuit.   |
| 4   | 40      | Weapon launch.  |

Simulation result is shown as Fig. 6.

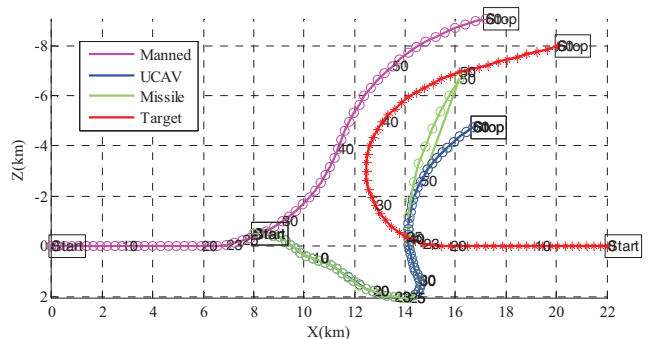


Figure 6. Ground trajectory of cooperative combat task simulation.

In this simulation, the UCAV maintains a 2km distance to the target while rounding to the rear of it. Simulation result shows that the UCAV keeps the distance to the target, and intercepts successfully. It can be concluded that the design of the maneuver library is effective in this imagined intercept task.

## VI. CONCLUSION

A scheme and design method for autonomous/semi-autonomous control system of UCAV is proposed in this paper. The scheme qualitatively classifies the common combat tasks into definite maneuvers and quantitatively defines parameters for them. Appropriate maneuvers are selected and executed to accomplish different tasks. With the ideas of linear and angular motion in flight mechanics, a hierarchical control structure is presented to facilitate the implementation of the maneuvers. Finally, two of the designed maneuvers are simulated, which verify that the design of maneuver control structure is effective. A detailed design for an imagined manned/unmanned cooperative intercept mission is proposed, which verifies the practicability of the maneuver library design.

A few problems remain unsolved in this paper. For example, the qualitative classification of the maneuvers is based on experience and the current maneuver library design might not fulfill some task requirements, which is not thoroughly studied in the design. The classification problem might be studied further in a quantitative sense and validated through the existing air combat experience. More detailed study is needed for actual air combat missions to improve and verify the design of the maneuver library further.

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