

# Development of a SysML Model and HIL Simulation of Multiple UAVs for Leader-Follower Collaborative Mission with Fixed Geometrical Formation

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## Abstract

A single Unmanned Aerial Vehicle (UAV) tends to be complex, expensive and completion of a task is often time consuming. Therefore, it is advantageous to use multiple UAVs for a task; such as surveillance rather than a single UAV. A collaborative team of autonomous UAVs can provide more effective operational capabilities to accomplish hard and complex task. But, the critical problem in realizing such multivehicle systems is to develop an efficient coordination and control algorithm to manoeuvre each vehicle, so that the multi-UAVs as a whole can produce flexible group behaviour.

This paper presents the design and development of a SysML based model and Hardware in Loop (HIL) Simulation Model for UAVs performing collaborative missions with fixed geometrical formation. To fulfill the collaborative mission, appropriate algorithms are identified and innovated which helped the Multiple UAVs to produce a flexible group. The collaborative mission is accomplished by using two UAVs (Leader and Follower) at a time. The Leader UAV will fly on a predefined flight path and the Follower UAV tries to maintain a fixed geometrical formation with respect to the Leader flight path. The coordination between Leader and Follower UAVs is maintained through a bidirectional wireless communication. Development of HIL Simulation Model for UAVs performing collaborative missions follows the V-model process.

Appropriate test strategy and phases are identified, to test the developed model. The behaviour of Leader-Follower UAVs is observed in mission planner at different positions of flight path. During the verification process for tight formation algorithm, the Follower UAV was unable to maintain the same altitude as the Leader UAV, while tuning with only throttle. This was corrected by tuning both throttle and pitch. As a part of future work, features, such as formation flying on more than two UAVs, simulating multiple UAVs in one PC and collaborative flying using two different unmanned vehicles can be incorporated.

**Key Words:** UAV, SysML, HIL, Collaborative Mission, Leader-Follower, Mission Planner

## 1. INTRODUCTION

Unmanned aerial vehicles (UAVs) are autonomous flying vehicles equipped with sensing devices and possibly weapons. However, current UAVs tend to be complex, expensive, time consuming for completing a task and often bulky. This has motivated us to develop a collaborative control of UAVs for a task like surveillance, rather than a single UAV.

Fig. 1 shows the block diagram of HIL simulation model for UAVs performing Collaborative mission. Such team-based operations include surveillance operations, battle damage assessment, space exploration, and scientific data gathering. Military aircraft, ground units, and naval forces use cooperative behaviour to benefit from mutual protection, concentration of offensive power, and simplification of control. A collaborative team of autonomous UAVs can provide more effective operational capabilities to accomplish hard and complex task, compare to the independent control of a UAV.

SysML is a general purpose graphical modeling language for System Engineering domain. It supports the specification, design, analysis, validation and verification of complex systems. These systems may

include hardware, software, processes, information, personnel and facilities. The language is designed to provide simple, but powerful constructs for modeling a wide range of system engineering problems. It provides graphical representations with a semantic foundation for modeling system requirements, behaviour and structure, which is used to integrate with other engineering analysis models. SysML based model assists in managing complex system development to improve the design quality by reducing error and ambiguity. There are different open source tools which are been used for complex system modeling like Papyrus and Topcase.

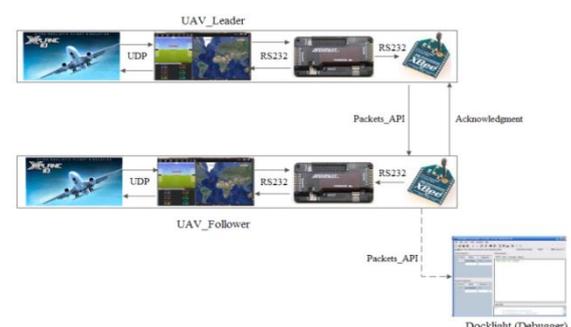


Fig. 1 Block Diagram of HIL simulation model

## 2. PROBLEM DEFINITION

The paper concentrates on SysML modeling and HIL Simulation of Leader-Follower autonomous UAVs and their collaborative missions with fixed formation. In formation flying, there are two types of formation: loose and tight. In loose formation, the follower may or may not maintain a geometrical formation. But in tight formation, the follower will maintain a geometrical formation. However, loose formation can work in low sampling rate and without any hardware limitations. The main aim of the paper is to design and develop a SysML based model and Hardware-in-loop Simulation leader-follower collaborative mission with fixed geometrical formation of UAVs.

## 3. DESIGN AND DEVELOPMENT

The development of HIL Simulation Model for UAVs is planned according to the system functionality, where the algorithms are identified and innovated. In autonomous flying, the attitude (roll, pitch and yaw) of UAVs is computed with respect to current location using DCM (Direction Cosine Matrix) algorithm. It calculates the orientation of a rigid body, with respect to the rotation of the earth by using rotation matrices. Rotation matrices are related to the Euler angles (roll, pitch, yaw), which describe the three consecutive rotations needed to describe the orientation. Sensors used in DCM algorithm are Gyroscope, Accelerometer and Magnetometer. The rotation matrix contains all the information needed to express the orientation of the plane with respect to the ground. It is also called as direction cosine matrix, because each entry is the cosine of the angle between an axis of the plane and an axis on the ground.

Based on the algorithms, SysML design has been carried out. The SysML model is designed using structure and requirement diagrams. The designed SysML model is not specific to any hardware and software platform. It is a versatile and reusable model. Implementation of HIL Model for UAVs performing collaborative missions is carried out using different hardware and software components. Appropriate changes in the autopilot firmware are carried out; based on the derived objectives. Finally, hardware implementation is carried out into four different phases.

### 3.1 Hardware Interfacing

Fig. 2 shows the interfacing of hardware blocks used in HIL Simulation Model for UAVs performing collaborative missions.

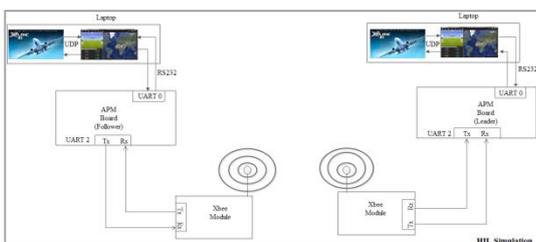


Fig. 2 HIL Simulation Model

The model shows three hardware blocks and two software blocks: APM (Ardu Pilot Mega) board, Xbee

module, laptop, X-plane flight simulator and mission planner which are used in HIL Simulation Model for UAVs performing collaborative missions. In HIL Simulation Model, the leader (APM board) will receive flight data from simulator through mission planner. The microcontroller will compute the flight data and will send a feedback signal to flight simulator through mission planner. Above process will be repeated for the follower APM board. The leader will also generate UAV packets which will be transmitted to Xbee module through UART (Universal Asynchronous Receiver Transmitter) -2 port, as shown in Figure 2. The follower (APM board) will read the packets from Xbee module through UART-2 port. Based on the received packets, follower will send feedback signals to flight simulator through mission planner.

### 3.2 Software Development

Following are the changes made in the arduplane firmware, in order to perform collaborative mission with fixed geometrical formation in HIL simulation.

#### HIL Simulation

The autopilot firmware in APM boards, by default, works in real-time flying. Therefore, in order to enable the HIL Simulation, HIL\_Sensors and HIL\_GPS should be enabled in the arduplane firmware.

#### Development of Loose Formation algorithm

First, define the collaborative mission and aircraft type. Second, in collaborative mission if the aircraft is leader, it will transmit the packets to follower. If the aircraft is follower, it will receive the packets transmitted by Leader UAV.

#### Development of Tight Formation algorithm

In tight formation the Follower UAV will maintain a predefined distance with Leader UAV by tuning the throttle and pitch respectively.

## 4. TESTING AND VALIDATION

For testing the developed HIL Simulation Model for multiple UAVs, a bottom-up integration testing approach is used. This is because without testing the lower layer (Layer-1) modules (HIL Simulation, UART-0 and 2 ports and Xbee) the Leader-Follower Collaborative Flying and Fixed Formation Flying modules cannot be tested. Therefore, the upper layers (Layer-2 and 3) modules are dependent on lower layer (Layer-1) modules, as shown in Fig. 3.

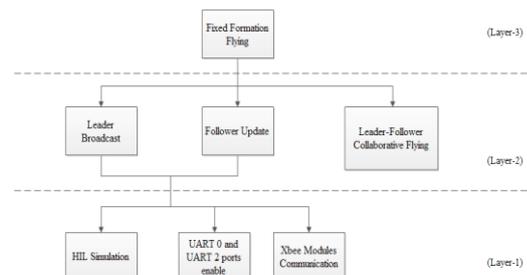


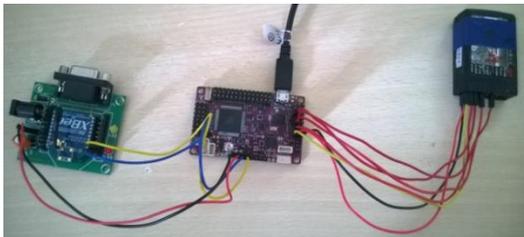
Fig. 3 Testing Hierarchy of HIL Simulation Model

In tight formation flying, the Follower UAV tries to maintain a predefined distance from the Leader UAV. If the follower falls back, then its ground speed will increase, so as to maintain the predefined distance.

The distance between leader and follower is equivalent to the distance between current waypoint and next waypoint of Follower UAV, which is displayed in the mission planner as Distance to waypoint (meters).

## 5. RESULTS AND DISCUSSION

Fig. 4 shows the system setup of Leader-Follower UAVs performing collaborative mission in HIL simulation.



**Fig. 4 Hardware Setup**

### 5.1 Results and Analysis

The geometrical formation and flight path of Leader and Follower UAV are observed while performing the collaborative mission. In the following sub-sections, analysis of the results is carried out using appropriate graphs generated from the recorded log files of collaborative mission.

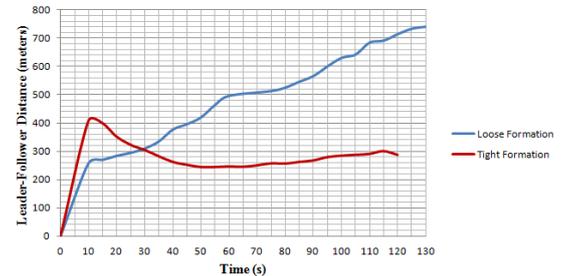
The leader will generate a packet in API mode and the packet will be transmitted to follower through Xbee-S1 module. The follower will verify the packet through CRC (Cyclic Redundancy Checking) and extracts the location of leader from the received packet. The extracted location will be assigned as next waypoint to the Follower UAV, if the Follower UAV is in guided mode.

#### Formation for Loose and Tight algorithm

The tightness of flight formation during collaborative mission is evaluated based on the distance between Leader and Follower UAVs, monitored at the follower's end. The graph showing the distance between Leader and Follower UAVs during collaborative mission, when loose and tight formation algorithms are implemented, is shown in Fig. 5.

In loose formation algorithm, the distance between leader and Follower UAVs increases with time. At 70s, the distance is 500 m in loose formation. In tight formation algorithm, the Follower UAV maintains a predefined distance with the Leader UAV. At 10 s the distance is 400 m and at 70 s the distance is 25 m

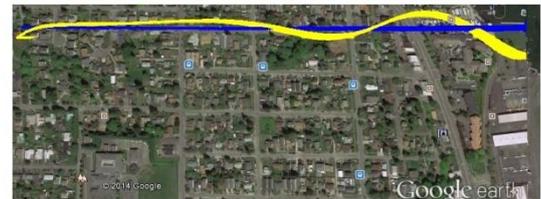
respectively. It is observed that when loose formation algorithm is implemented, the Follower UAV is unable to reconfigure the distance with the Leader UAV but during tight formation, the Follower UAV maintains a predefined distance with the Leader UAV.



**Fig. 5 Comparison between Loose and Tight Formation Algorithm**

#### Multi-UAV's Flight Path for Tight Formation

The flight path obtained from the recorded log file of a tight formation collaborative mission has been superimposed on Google earth, as shown in Fig. 6.



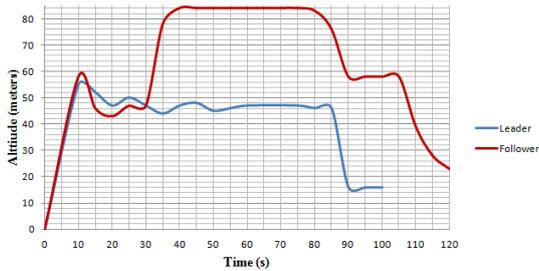
**Fig. 6 Leader and Follower Flight Path**

From Fig. 6 it is observed that the follower flight path is not same compared to leader flight path. The latitude, longitude and altitude information of the flight path is extracted from the log file. It is observed that at each point of the longitude and latitude (leader), there is a deviation. The objective of tight formation algorithm is to minimize this deviation during collaborative mission.

For the particular flight path (Fig. 6) discussed in this section, the maximum deviation in longitude and latitude is approximately 37 m and 30 m respectively. The minimum deviation with respect to longitude and latitude is around 4 m and 2 m respectively. The maximum deviation occurs at the beginning of the collaborative mission because the Follower and Leader UAV are not necessarily started at the same location or at same time. During the collaborative mission the Follower UAV tries to reduce the deviation from the leader's flight path.

Fig. 7 shows the altitude of Leader and Follower UAV at different time instants, for the particular flight path. During the collaborative mission the Follower UAV should maintain same altitude with Leader UAV.

The maximum altitude deviation of Follower UAV is 83 m and the minimum deviation is 0 m respectively. During the formation reconfiguration the follower tries to reduce the distance with the Leader UAV by increasing the ground speed which affects the altitude overshoot the follower aircraft's elevator is tuned to pitch down, if the follower goes above the leader's altitude.



**Fig.7 Leader-Follower Altitude in Tight formation**

According to the test cases, the developed model has been tested and evaluated on different flight missions.

## 6. CONCLUSIONS

According to the objectives, hardware and software specifications as well as the functional and non-functional requirements of HIL Simulation model have been derived. To develop a leader-follower collaborative flying, appropriate algorithms were identified and innovated. The algorithms are DCM algorithm, loose formation algorithm and tight formation algorithm. A model based approach (SysML) is used for designing the HIL Simulation Model.

In the autopilot firmware appropriate changes were made, to run the HIL Simulation Model. The developed model is implemented in four phases. The phases have been tested by following bottom-top test strategy and deriving appropriate test cases for verifying the test results. Finally, based on the test results and functional requirements, the HIL Simulation Model has been validated.

- The collaborative flying in HIL simulation follows two algorithms for geometrical formation, namely loose and tight formation.
- The loose formation is able to maintain the geometry, but it is unable to maintain distance between leader-follower. The above discussed problem is resolved by tight formation algorithm which maintains both the geometry and leader-follower distance during the collaborative flying.

## 7. FUTURE WORK

Following are the future works:

- The developed HIL Simulation Model of UAVs for leader-follower formation flying is implemented by using two UAVs.
- By simulating multiple UAVs in one personal computer, usage of hardware resources can be reduced and monitored by using the collaborative flying which will be much easier.
- The developed model will be tested in real-time scenario using same hardware components except Xbee-S1 module, which is not suitable for real time long range needs. Therefore Xbee-S1 Pro module can be used.

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