Study of Target Centric Cyclic Pursuit for MAVs using Hardware In Loop Simulator

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Target centric cyclic pursuit is a decentralized strategy developed for monitoring a point of interest with multiple autonomous vehicles. This strategy has been implemented for the vehicles modeled as unicycle. Before implementing such cooperative missions for miniature aerial vehicles they need to be verified considering complete dynamics of the vehicles and practical issues such as communication loss, wind, etc. The work presented in this paper extends the implementation of Target Centric Cyclic Pursuit strategy considering complete 6-DOF aircraft model. Also Hardware In-loop Simulator has been used to verify the effectiveness of strategy considering real time simulation of the 6-DOF model with communication as actual hardware in the loop and Dryden wind model in the flight simulation.

I. Introduction

Multi agent systems offer many advantages over single agent systems for missions such as surveillance, search and rescue, scientific data gathering, convoy protection etc. In such applications it is often required to monitor a target of interest continuously from all the directions. For the work presented here the target centric cyclic pursuit (TCCP) strategy has been considered. With this strategy, the agents move along a target centered circle with a uniform distribution of relative positions on the orbit.

Cyclic Pursuit algorithms have been extensively studied in literature. In cyclic pursuit a group of agents start from arbitrary initial positions and eventually attain an equilibrium where they fly behind each other. Each agent communicates its own position information to with a neighbouring agent. This idea is directly derived from the linear cyclic pursuit case which results in rendezvous of the agents having linear integrator dynamics at a centroid.

The linear cyclic pursuit when extended to agents having non-linear dynamics (e.g., unicycle model) results in non linear basic cyclic pursuit. Now at equilibrium instead of rendezvous at a centroid, the agents move along a circle provided their velocities are the same. If the velocities are not the same, concentric circles are obtained. This strategy can be directly be used on MAVs for conducting cooperative missions, but the with the limitation that the center of the circle depends on the initial positions of the agents and thus there is no direct control on where in space the consensus is reached.

In order to have the control on the center of the circle formed by non-linear basic cyclic pursuit, a control strategy called Implicit Leader Cyclic Pursuit (ILCP) can be used. In this strategy the implicit leader MAV follows a virtual leader point that divides the line joining the center of the center to the last MAV of the formation in a fixed ratio (called the camouflage factor). The authors have shown that at equilibrium, the agents move in a circle around a fixed center. One disadvantage in this control strategy is that there is a implicit leader in the formation and the formation depends on the leader agent’s performance. The TCCP strategy overcomes this limitation as it is a completely decentralized strategy for monitoring a target with the assumption that all the vehicles have information about the target. Since the TCCP strategy is applicable for agents having a unicycle model it can be adopted for fixed wing MAVs (and ground vehicles) which is the primary focus of the work presented here.

For the practical implementation several challenges both of hardware and software arise and need to be addressed. A major challenge for flight demonstration of cooperative missions is the implementation of an effective communica-

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tion scheme between the MAVs and the ground station to ensure cooperation. Though in computer simulations a good insight into the performance related aspects of cooperative strategies can be analysed, details such as communication bandwidth, packet collisions, packet loss, etc. are generally not considered. These issues are of paramount importance for implementation and can severely limit the effectiveness of the cooperative strategy being implemented. With this in mind the Hardware-in-Loop Simulator (HILS) system has been used for simulating cooperative missions and to study the tolerance of the TCCP strategy to practical issues such as communication losses and wind effects. Some preliminary verification of the TCCP strategy via simulation results using both HILS and 6-DOF simulations has been done previously.

The paper is organised as follows: Section II describes the cyclic pursuit based target tracking strategy. A brief description about the HILS system and its components is given in Section III. Section IV presents simulation results for tracking a stationary target with and without wind, with reduced inter-MAV communication rates and for tracking of a moving target. Section V presents concluding remark and future work.

II. Target Centric Cyclic Pursuit

Target Centric Cyclic Pursuit (TCCP) strategy is a cyclic pursuit based target monitoring strategy. Cyclic pursuit is a simple consensus seeking strategy in which vehicles are numbered from 1 to \( n \), where \( n \) is the number of vehicles. Each vehicle \( i \) follows its neighbour vehicle \( i - 1 \). For initial analysis the unicycle model has been assumed for each vehicle, which closely represents the kinematics of a wheeled robot or a fixed wing aerial vehicle. Considering applications such as aerial reconnaissance the TCCP strategy has also been considered for application on MAVs. To simulate a TCCP mission for MAVs, the MAVs are represented by complete 6-DOF aircraft model in both MATLAB and HILS simulations.

Consider a group of \( n \) vehicles employed to track the target. The kinematics of each vehicle are modeled as:

\[
\dot{x}_i = V_i \cos(h_i), \quad \dot{y}_i = V_i \sin(h_i), \quad \dot{h}_i = \omega_i
\]  

where \( P_i = [x_i, y_i]^T \) represents the position of vehicle \( i \), \( h_i \) represents the heading angle of the vehicle \( i \) with respect to a global reference frame and \( V_i \) and \( \omega_i \) represent the linear speed and angular speed of the vehicle \( i \) respectively. We assume that the vehicle \( i \) is moving with constant linear speed, that is \( V_i \) is constant and the motion of the vehicle \( i \) is controlled using the angular speed, \( \omega_i \).

![Figure 1. Positions of the vehicles in a target centric frame](image)

It is assumed that each vehicle \( i \) has the information about the target position and \( i - 1 \)th vehicle’s position. Consider the target to be located at point \( P \) as shown in Fig. 1. The classical cyclic pursuit law has been modified for target enclosing problem such that vehicle \( i \), positioned at \( P_i \), follows not only \( i - 1 \)th vehicle at \( P_{i-1} \) but also the target at \( P \). Let \( \rho \) be a constant, which decides the weight vehicle \( i \) gives to the target information over the information of the vehicle \( i - 1 \). So each agent \( i \) follows a virtual leader located at the point \( P'_{i-1} \) which is a convex combination
of $P$ and $P_{i-1}$. The point $P'_{i-1}$ is calculated as

$$P'_{i-1} = \rho P_{i-1} + (1 - \rho) P$$

(2)

where $0 < \rho < 1$. Since we are considering a stationary target, we assume a target centric reference frame (refer Fig. 1). The variables in Fig. 1 are: $r_{it}$ – Distance between $i^{th}$ vehicle and the target, $r_i$ – Distance between $i^{th}$ vehicle and $i - 1^{th}$ vehicle, $f_i$ – angle made by the vector $r_{it}$ w.r.t reference $f_{i-1}$ – angular separation between $i^{th}$ vehicle and $i - 1^{th}$ vehicle, and $\phi_i$ – angle between the heading of $i^{th}$ vehicle and modified LOS $P_i P'_{i-1}$.

The control input to the $i^{th}$ vehicle, that is, the angular speed $\omega_i$, is defined as

$$\omega_i = k_i \phi_i$$

(3)

where, $k_i > 0$ is the controller gain.

The vehicles are assumed be homogeneous in the sense that all of them move with same linear speed $\rho$ and controller gain. So $V_i = V$ and $k_i = k$ for all $i$. With the control law (3), the system of $n$ vehicles with kinematics (1) settles to a circular formation about the target. The radius of the circle $R$, inter vehicle distance $R_{aa}$ and the angular separation between two consecutive vehicles $f_i^{i-1}$ at equilibrium are given by:

$$R = \frac{V}{k \phi_{eq}}, \quad R_{aa} = 2R \sin \left( \frac{\pi d}{n} \right), \quad f_{i}^{i-1} = 2 \pi \frac{d}{n},$$

(4)

where,

$$\phi_{eq} = \frac{\pi}{2} - \sin^{-1} \left( \frac{\rho \sin \left( \frac{2 \pi d}{n} \right)}{\sqrt{1 + \rho^2 - 2 \rho \cos \left( \frac{2 \pi d}{n} \right)}} \right).$$

(5)

Thus at equilibrium, the vehicles arrange themselves in a formation around the target. This formation of $n$ vehicles can be described by a regular polygon $\{n \}, d \in \{1, 2, ..., n - 1\}$. For example possible formations in case of three vehicles are, with $d=1,2$, as shown in Fig. 2.

![Possible formations for three MAVs.](image)

**Figure 2.** Possible formations for three MAVs.

### A. TCCP with 6-DOF model

The TCCP strategy is extended to Miniature Autonomous Vehicles (MAVs), each represented by a 6-DOF model. The flight model is based on the wind tunnel data provided by National Aerospace Laboratories, Bangalore, India. The
flight model is programmed in MATLAB and Runge-Kutta fourth order method is used to carry out the simulation. The MAV auto-pilot code for level flight has three main parts - Altitude control, Airspeed control and Heading control. The TCCP strategy is implemented in Heading control part using the command as discussed below. The MAV autopilot requires three commands: the Airspeed command $V_c$, the Altitude command $Alt_c$ and a heading command $\chi_c$ which in turn generates an inner loop roll attitude command $\phi_{mav,c}$. The commands given to the autopilot of the $i^{th}$ MAV to implement the TCCP are $V_c = V$, $Alt_c = h_d$. Thus, the velocity and the altitude are held constant, and the Heading control or the turn rate as required by the TCCP law is achieved by rolling. The altitude is held constant to obtain a planar situation equivalent to TCCP of planar unicycle vehicles. To achieve the desired turn rate, we approximate the heading angle rate $\dot{\chi}_i$ as

$$\dot{\chi}_i = \frac{g}{V} \phi_{mav,i}$$

where $g$ is the acceleration due to gravity. We command the roll angle $\phi_{mav,c}$ to obtain a desired turn rate. Since the desired heading rate for vehicle $i$ is $\dot{\chi}_i = \omega_i = k\phi_i$ as given in (3), the commanded roll angle is given as

$$\phi_{mav,c} = \frac{g}{V} k\phi_i$$

The structures of the individual controllers implemented for altitude hold, heading hold and airspeed hold are similar to the autopilot structures by Beard et. al\textsuperscript{8} for the same tasks.

**Implementation of TCCP**

For implementing the target centric cyclic pursuit strategy\textsuperscript{1} on HILS\textsuperscript{10} for three MAVs, the On-board computers (OBC) of all the MAVs have been programmed to follow the virtual leader point defined using parameter $\rho$. In order to compute the heading towards the virtual leader each MAV$_i$ has to know the position of MAV$_{i-1}$, and thus it is necessary that MAV$_{i-1}$ must communicate its current location to MAV$_i$ at regular intervals as the mission progresses. This is schematically shown in Fig. 3.

This paper restricts to the use of 3 MAVs for the sake of convenience in obtaining experimental insights into the properties of the control strategy for different values of $\rho$, initial conditions and final formation obtained. In order to achieve this three separate 6-DOF model flight simulations of the three MAVs have to be run in real time on HILS. Since the measurement data of onboard sensors of the MAV, is simulated as a part of the flight simulation, it must be conveyed at correct rates and in the correct sentence formats. This is done to exactly mimic the sensors in order to achieve results closer to the reality of actual flight demonstrations. This is discussed in greater detail in the following section.
III. Hardware in Loop Simulator Architecture

The HILS system used for this paper was first developed for simulating three MAVs in real time and some mission involving three MAVs were simulated. Later the system was extended to accommodate four MAVs and some better communication strategies such as Carrier Sense Multiple Access-Collision Avoidance or CSMA-CA were incorporated to improve the performance of the communication network between the MAVs and the ground station. This system has been further extended to simulate eight MAVs along some recent improvements such as support for real time monitoring and recording of flight parameters, a Dryden model simulating wind, etc. The Dryden model block available in Simulink was used to include wind into the flight simulation to study the effects of wind on the cooperative missions.

Hardware and Software Description

The HILS system is primarily divided into two parts (shown in Fig. 5): The simulated components and the actual hardware subsystems present in the simulation loop. Functionally the HILS system comprises of the components shown in Fig. 5. A brief description of each component is given below.

Simulation Environment

**Host PC:** The Host PC is a desktop computer equipped with an ethernet port and is used to modify and build the flight simulation. For simulating eight aircraft the entire simulation is abstracted as two identical Simulink®v7.7 block diagrams, consisting of embedded MATLAB®R2011a functions for various tasks. Both these block diagrams simulate four MAVs each, and can be built with different initial conditions for each MAV. Using the host PC the block diagrams are built and compiled into C programs using a suitable C compiler such as Microsoft®Visual C++®2008. After compilation these programs are loaded on the two target computers using a MATLAB®script via ethernet connections as shown in Fig. 5. The host PC can also run a Simulink®model which has been made for receiving and recording the runtime simulation data sent by the target PC via User Datagram Protocol (UDP) packets. The data is stored in a MATLAB®work space for future analysis after the simulation is completed. It also shows real time running plots of the MAV states such as pitch, roll, yaw, velocity, altitude, etc. which help in easy tuning of the autopilot gains during runtime. It should be noted that the flight model used for simulation is based on wind tunnel data obtained from National Aerospace Laboratories, Bangalore.

**Target PCs:** Target PCs are the computers on which the Real-Time Operating System (RTOS) is run for real time simulation of the cooperative mission. The RTOS used here comes bundled with the MATLAB®and is called the xPC Target™Rapid Prototyping System v5.0. It is run using bootable CD-ROMs on the Target PCs. Each target PC runs the flight simulation for four MAVs and generates the corresponding sensor data for the MAVs’ On-board Computers (OBCs) in appropriate formats as shown in Fig. 5. Also the servo-motors actuated by the OBCs give an analog feedback which is converted to its digital equivalent using an Analog to Digital Converter (ADC) card on each target PC. This feedback goes as input to the flight simulation hence closing the simulation loop. The sensor information generated by each target PC includes the GPS and IMU sentences which are serially communicated to the OBCs at appropriate baud-rates at regular intervals. Since each MAV needs two serial ports to communicate with the Target PC, in order to simulate four MAVs on each target PC an eight port serial card has been used. The altitude and airspeed states in the flight simulation of each MAV is converted to equivalent pressure sensor data and is then converted to analog voltages with proper scaling. This is done using a Digital to Analog Converter (DAC) card on each target PC. The analog pressure sensor voltages are then given as sensor outputs to the OBC. The specific interface cards used on the Target PC for the information exchange with the hardware in the loop are as shown in Fig. 6.

**Hardware In The Loop**

**On-board Computers:** The peripheral interfacing details of the OBCs used with this HILS system are as shown in the Fig. 6. The OBC has serial interfaces with the target computer through two of its serial ports (for GPS and IMU data) and is connected to the XBee-Pro®communication module on the third serial port. It is programmed to extract data from GPS sentences received in the NMEA format in accordance to the EM-406A GPS receiver module, and IMU data sentences (proprietary sentences of Microstrain®3DM-GX2®IMU). The analog voltages from the target PC corresponding to pressure sensor data for airspeed and altitude are connected to the ADC inputs of the OBC. The on-board computer produces pulse width modulated (PWM) signals on its PWM channels to operate servo motors.
Figure 5. Block diagram of the HILS system for real time simulation of cooperative missions of eight MAVs.

Figure 6. Block diagram of one of the target PCs

for actuation of the aircraft control surfaces (Elevator and Ailerons) and to run the brush-less DC (BLDC) motor for generating propeller thrust (Throttle). In the HILS the BLDC motor is not used as it needs very high current and a servo-motor is used instead to simulate throttle. This is acceptable as both servo motors and BLDC motors use similar PWM signal inputs for actuation control. The OBC uses the XBee-Pro® RF modules for communicating with other MAVs’ OBCs and the Ground Station during the real time simulation.

Communication Network : The general network graph structure required for simulating the target centric cyclic pursuit mission by three MAVs on the HILS is shown in Fig. 3. The communication module used here is the XBee-Pro®RF module. It is a wireless serial communication module, which has sufficient range for actual flight demonstrations and supports communication via addressed packets with checksum and acknowledgements. To use packet based communication the XBee-Pro®RF modules of all the MAVs and the ground station have been configured in the Application Programming Interface (API mode), i.e., all the communication links shown in Fig. 4 utilise this mode.

In the API mode the XBee-Pro® module identifies addressed packets and verifies checksum. Thereafter either the entire correct and complete packet is accepted or in the case of error or data loss, the entire packet is rejected. This avoids mixing of data from different packets at the ground station. Also in API mode, the transmitting XBee® module gets an acknowledgement from the receiving end and hence loss of data packets can be detected. In order to transmit API packets the correct construction of API packet and calculation of checksum is necessary before transmission to ensure proper communication. For the HILS simulations in this paper the communication packet payload mainly consists of GPS latitude and longitude data.

The XBee-Pro® module is a half duplex communication device, i.e., transmission and reception is not possible simultaneously. Also since these modules operate at the same signal bandwidth, packet collisions can occur and must be avoided. Some packet collision avoidance strategies such as Time Division Multiplexing (TDM)

Ground Station: The ground station used for monitoring the MAV flight parameters during HILS simulations is a C++ application program, initially developed for a single MAV mission. The ground station application has been modified so that it is compatible with API packets containing GPS information of the MAVs, and so that it can plot...
the GPS position on receiving the packet from the MAV and verifying a correct checksum. On receiving position data from each MAV’s packets, the ground station plots the current position of the MAV on the map with its corresponding coloured spot. The ground station also allows tuning gains of autopilots programmed on the OBC during the real-time HILS simulations.

IV. Simulation Results

In this section simulation results for tracking stationary target and for moving target have been presented.

A. Stationary target monitoring

Figure 7. Unicycle model simulation trajectories for both cases of initial positions with $\rho = 0.5$. (⋄: initial positions, ⋆: final positions)

Figure 8. 6-DOF MAV model simulation trajectories for both cases of initial positions with $\rho = 0.5$. (⋄: initial positions, ⋆: final positions)

A set of three MAVs moving with a constant speed of 15 m/s and controller gain of 0.2 have been considered, starting from random initial positions. Simulation is run for different values of $\rho$ and for two different initial positions. Fig. 7, 8 and 9 shows the trajectories of the MAVs with point mass model, Six DOF model and HILS simulation respectively with $\rho = 0.5$ for both initial positions. It can be observed from the figures that the MAVs are able to capture the target with uniform distribution. The trajectories of the MAVs depends on the model used, number of vehicles, initial positions of the vehicles and the parameter $\rho$. Table 1 and 2 shows different parameters at steady state for the two initial positions with different values of $\rho$. For a given $\rho$, if the final formation is same with three different implementations then final radius of the circle matches closely in all three implementations. Also for a given $\rho$ and
Figure 9. HILS simulation trajectories for both cases of initial positions and $\rho = 0.5$.

Table 1. Steady state parameters for first set of initial conditions with variation of $\rho$

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Table 2. Steady state parameters for second set of initial conditions with variation of $\rho$

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final formation, theoretical results obtained$^1$ match with the simulation results.
Effect of inter-MAV update frequency on TCCP

In most practical scenarios, for various reasons there can be an intermittent communication failures leading to packet loss among agents. This is unavoidable and the cooperative strategy must be able to tolerate such practical constraints. With this motivation the simulations results presented in this section give an idea about the smallest inter aircraft update rate required to ensure proper target tracking and equilibrium formation with the TCCP law.

Most GPS modules available have a position update frequency in the range of a few Hz. The GPS module simulated in the HILS has a position update rate of 1Hz. Since the inter aircraft communication conveys position information of each aircraft to its neighbour, the ideal rate of sharing this information is rate is 1Hz.

<table>
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<th>Revolution time period (Seconds)</th>
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For three MAVs moving with a constant airspeed of 14.5 m/s and inter aircraft update rate of 1Hz, the time taken for one revolution around the target, with four different values of rho is as given in table 3. It is observed that if the inter MAV communication update period is lesser than approximately half the time taken for one complete revolution around the target, the MAVs are able to maintain the target at the center of their orbit, and their relative positions are uniformly distributed on the orbit as per the formations discussed previously. But the orbit is not exactly circular in nature. The various orbits observed with \( \rho = 0.8 \) for different inter agent update periods are shown in Fig. 10. If the inter agent update period is longer than the time taken for half the revolution around the target, then the equilibrium formation is not maintained and the MAVs loiter around the target.

It can be inferred from these results that the inter-MAV update period can be increased considerably (upto 10 times for \( \rho = 0.8 \) and 3 MAVs) with an acceptable performance. Thus a larger inter-MAV update periods means that the TCCP mission can be implemented for large number of agents. It also reduces risk of packet collisions as transmission instants of individual MAVs can be well separated. Also more time is available per individual aircraft for transmission. This allows more information to be shared among the MAVs and there is a scope for implementing more complex cooperating tasks which require larger amounts of data to be communicated.

Effect of wind

Since the wind is a major factor in deciding performance of cooperative algorithms, Dryden wind model has been used in the simulation. To study the effect of wind on the performance of a mission using the TCCP strategy, HILS simulations have been carried out for three wind speed conditions: 3.5 m/s, 5 m/s and with 8m/s. In all the three cases \( k = 0.2 \) and the values of \( \rho = 0.1, 0.4 \) and 0.8 have considered (Fig. 11, 12 and 13). The simulation with no wind which is the ideal case is shown in Fig. 9. From the Fig. it can be observed that this strategy works better for lower wind speeds and smaller \( \rho \) values. Also with increase in wind speed error in radius as well as inter agent distances increase. At lower wind speed uniform distribution is disturbed but the MAVs are still able to fly near the target position. The MAVs are unable to maintain the target at the center of the formation. At wind speed = 8m/s, the MAVs are unable to get into formation and drift away from the target in the direction of the wind.

Moving Target Simulations

Some preliminary work has been done to investigate the possibility of using TCCP strategy to capture a moving target assuming that all the MAV’s have position information of the target. The target is assumed to move with a velocity 2 m/s along a circle of radius 300 meters. The three MAVs have been placed randomly and moving with a speed of 15m/s, controller gain of 0.2 and \( \rho = 0.2 \). Fig. 14, Fig. 15 and Fig. 16 show the trajectories of vehicles tracking a moving target simulated as a point mass model, 6-DOF model and a HILS simulation respectively. From the plot, we observe that the vehicles get into a formation about the moving target and continue to enclose the target maintaining the formation.
V. Conclusions and Future Work

The use of realistic MAV models in simulations showed minor deviations from the ideal kinematic behaviour predicted by the developed theory. When the final formation is the same for point mass model, 6-DOF simulation and HILS simulations, the steady state parameters have comparable values. Effect of lower inter-MAV update rates on the performance of the TCCP based cooperative mission has also been investigated. It has been observed that there is a considerable scope for reduction of inter-MAV communication and some possible benefits of the same have been discussed. The lowest communication update rates indirectly give an idea about the tolerance of the TCCP strategy to the loss of communication packets and failure. To study the effect of wind on the mission, the Dryden wind model has been simulated in real time as a part of the flight simulation. For low wind speeds of up to 5 m/s it is observed that MAVs are able to move near the target with reasonably periodic orbit. Future work could be to improve the algorithm to reduce deviation from target due to wind. From the simulation results it is clear that the TCCP strategy has potential to track a slow moving target. Further analysis in this direction is an objective of future research.
Figure 11. TCCP HILS simulation with $\rho = 0.1$ and wind speed=3m/s towards north

Figure 12. TCCP HILS simulation with $\rho = 0.4$ and wind speed=3m/s towards north

Figure 13. TCCP HILS simulation with $\rho = 0.8$ and wind speed=3m/s towards north

Figure 14. Point mass model simulation for $\rho = 0.2$ and a moving target ($\Diamond$: initial positions, $\star$: final positions)

References


Figure 15. 6-DOF model simulation for $\rho = 0.2$ for a moving target (⋄: initial positions, ⋆: final positions)

Figure 16. HILS Simulated trajectories for case1 and $\rho = 0.2$ for a moving target.


