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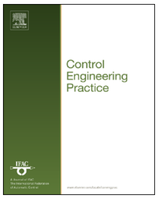

Coordinated trajectory planning for efficient communication relay using multiple UAVs

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ABSTRACT

This paper investigates the use of small UAVs as communication relay nodes for expanding communication links and improving communication quality for a fleet of naval vessels. This paper firstly deals with the UAV deployment for stationary communication nodes, and then, proposes a decentralised nonlinear model predictive trajectory planning strategy for a dynamic environment. By exploiting motion estimates of vessels and states of UAVs, the trajectory planning algorithm finds a control input sequence optimising network connectivity over a certain time horizon. Numerical simulations are performed for both stationary and manoeuvring vessels to verify the feasibility and benefit of the proposed approach.

1. Introduction

Traditionally communication relay was considered a secondary mission on a platform deployed on another main mission. However, with the advent of lightweight, robust and autonomous platforms as well as wireless networking technologies, UAVs (unmanned aerial vehicles) can now perform this relay mission. UAV communication relay is intended to replace the legacy radios currently being used on tactical size UAVs such as Predator, Fire Scout, and Hunter, among others (Samad, Bay, & Godbole, 2007). Regarding the airborne communication relay payload, Grumman (2013) developed a communication relay package to provide four communication software programmable channels, which can be configured to provide ground to ground, air to air, or ground to air relay. Thales (2013) is also developing a dedicated version of the LMAR (Lightweight Multiband Airborne Radio) for the British Watchkeeper program. This study is motivated by using such a capability for expanding communication links and improving communication quality, primarily for a fleet of ground or navy vessels. An airborne relay can effectively connect to units operating over the horizon, beyond normal communication range, or under limited satellite communication environments. However, even if the equipment development is relatively mature, and considerable research on a mobile ad hoc networking has been performed for ground robot teams (Hsieh, Cowley, Kumar, & Taylor, 2008; Pimentel & Campos, 2003; Wagner & Arkin, 2004), where to locate UAVs for efficient relay is still a pending problem due to UAV's dynamic and operational constraints.

The feasibility study to use UAVs as communication relay is performed mainly in support of a battlefield information transmission system initiative (Hampel & DiPierro, 1996). The main objective of this program was to provide beyond line-of-sight communications within an area of operations without using scarce satellite resources. Cerasoli (2007) assessed the practical effectiveness of a UAV communication relay in an urban area using the ray tracing method. Kim, Silson, Tsourdos, and Shanmugavel (2011) proposed a path planning strategy of multiple UAV for communication relay between a ground control station and a friendly fleet. This work considered communication range and other constraints such as maximum curvature and no fly zone; it was devoted to designing off-line trajectories of UAVs with known motion planning of a friendly fleet. Basu, Redi, and Shurbanov (2004) investigated the optimal number and placement of UAVs as well as heuristic flocking algorithm, in order to connect all mobile ground nodes. In this work, connectivity between nodes is characterised by only communication range. Zhu, Swindlehurst, and Liu (2009) proposed an online optimisation algorithm of the location and movement of UAVs to improve the connectivity of a wireless network. They considered a realistic wireless communication model, four different types of network connectivity, and the speed constraints for optimal UAV movement. However, this study investigated the effect of a single UAV only, and the turning

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constraint of the UAV is not addressed, resulting in discontinuous trajectories.

With this background, this paper proposes high-level deployment algorithms to optimise the trajectory of multiple UAVs for improving the connectivity of a wireless network among a fleet of vessels considering various operational and dynamic constraints of the UAV. In this study, network connectivity is modelled by the context of MANETs (Mobile Ad hoc NETworks) based on global message connectivity. This connectivity is defined by the probability of successful propagation of commands to all the distributed vessels. Typically, a communication system of vessels has enough transmit power to be able to communicate with one another amongst a fleet within a bounded area in a maritime environment. However, as the number of vessels in a fleet increases, the communication network complexity increases significantly; thus ensuring network connectivity for sharing information efficiently amongst them becomes a challenging issue. In such a case, it is required to determine which links should be used to distribute information throughout the entire network such that (i) all the nodes are connected and (ii) the overall network connectivity is maximised in terms of global message connectivity.

To achieve aforementioned objectives, the concept of minimum spanning tree (MST) from graph theory (Diestel, 2005) is used to obtain the highest probability of a successful transmission using minimum possible links. To further improve network connectivity along with this MST, UAVs equipped with wireless transceivers can be involved as communication relay in a wireless ad hoc network, whilst flying over a fleet of vessels and communicating with other ground nodes as well as other UAVs. Exploiting UAVs is advantageous in that (i) there is less signal attenuation in ground-to-air communication compared to ground-to-ground case suffering from obstacles such as terrain or waves; and (ii) UAVs are generally faster than vessels and thus can be rapidly deployed whenever needed, e.g. when there is a partial communication link failure. It is worth noting that UAVs that are able to hover, usually rotorcrafts, might be a good choice to be deployed for stationary communication nodes. In this case, vehicle speed and operational ranges are limited. On the other hand, a fixed-wing UAV can be much faster and operated in much wider areas than those of rotorcrafts; however, it has dynamic and kinematic constraints represented as the minimum (or stall) velocity and turning radius. These constraints should be addressed for the use of fixed-wing UAVs as communication relay.

This paper firstly deals with the UAV deployment for stationary communication nodes, which finds the fixed optimal location of UAVs ensuring the maximum network connectivity. Then, considering movement of vessels and constraints of the fixed-wing UAV in a dynamic environment, this study proposes a nonlinear model predictive control (NMPC) based trajectory planning strategy. By exploiting motion estimates of vessels and states of UAVs, the NMPC algorithm finds a control input sequence for a certain time horizon which optimises network connectivity. Collision between UAVs is also included in the cost function of the optimisation process. In this NMPC frame, since it would be almost infeasible to optimise the control inputs of entire multiple UAVs in a centralised system at once, this study uses a fully decentralised NMPC concept; each UAV optimises its controller individually based on the future state predictions of the other UAVs. Numerical simulations using multiple UAVs as communication relay are performed for both stationary and mobile node case with a fleet of vessels to verify the feasibility and benefits of the proposed approach.

The overall structure of this paper is given as follows. Section 2 explains UAV, vessels and sensor model and the tracking filter used in this study. Section 3 introduces a wireless communication model and modelling of network connectivity using the concept of MST. Section 4 proposes optimisation algorithms for UAV position and trajectory to maximise network connectivity. Section 5 presents numerical simulation results to communication relay scenarios depending on the number of vessels and available UAVs. Lastly, conclusions and future work are given in Section 6.

2. Problem definition

2.1. UAV dynamic model

Assuming that each UAV has a low-level flight controller such as SAS (Stability Augmentation System) and CAS (Controllability Augmentation System) for heading and velocity hold functions, this study aims to design guidance inputs to this low-level controller for efficient communication relay. Consider a two-dimensional UAV kinematic model (Kim, Oh, & Tsourdos, 2013) as

$$\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{\psi} \\ \dot{v} \\ \dot{\omega} \end{pmatrix} = f(\mathbf{x}, \mathbf{u}) = \begin{pmatrix} v \cos \psi \\ v \sin \psi \\ \omega \\ -\frac{1}{\tau_v} v + \frac{1}{\tau_v} u_v \\ -\frac{1}{\tau_\omega} \omega + \frac{1}{\tau_\omega} u_\omega \end{pmatrix} \tag{1}$$

where $\mathbf{x} = (x, y, \psi, v, \omega)^T$ are the inertial position, heading, speed and yaw rate of the UAV, respectively. τ_v and τ_ω are time constants for considering actuator delay, which can be determined experimentally by analysing the characteristics of the UAV autopilot. $\mathbf{u} = (u_v, u_\omega)^T$ are the commanded speed and turning rate constrained by the following dynamic limits of fixed-wing UAV:

$$|u_v - v_0| \le v_{max} \tag{2}$$

$$|u_\omega| \le \omega_{max} \tag{3}$$

where v_0 is a nominal speed of the UAV. The continuous UAV model in Eq. (1) can be discretised by Euler integration into

$$\mathbf{x}_{k+1} = f_d(\mathbf{x}_k, \mathbf{u}_k) = \mathbf{x}_k + T_s f(\mathbf{x}_k, \mathbf{u}_k) \tag{4}$$

where $\mathbf{x}_k = (x_k, y_k, \psi_k, v_k, \omega_k)^T$, $\mathbf{u}_k = (u_{vk}, u_{\omega k})^T$, and T_s is a sampling time. Note that the effect of wind is not considered in this study.

2.2. Marine vessel and sensor model

This study considers acceleration dynamics to estimate the movement of marine vessels or ground vehicles. This dynamic model defines the target acceleration as a correlated process with a decaying exponential autocorrelation function, which means that if there is a certain acceleration rate at a time t then it is likely to be correlated via the exponential at a time instant $t+\tau$. A discretised system equation for the acceleration model is thus expressed in the form

$$\mathbf{x}_k^v = F_k \mathbf{x}_{k-1}^v + \eta_k \tag{5}$$

here the state vector is $\mathbf{x}_k^v = (x_k^v, \dot{x}_k^v, \ddot{x}_k^v, y_k^v, \dot{y}_k^v, \ddot{y}_k^v)^T$, and where η_k is a process noise which represents the acceleration characteristics of the target. The state transition matrix F_k is given by

$$F_k = \begin{bmatrix} 1 & T_s & \Phi & 0 & 0 & 0 \\ 0 & 1 & \frac{(1 - e^{-\alpha_v T_s})}{\alpha_v} & 0 & 0 & 0 \\ 0 & 0 & e^{-\alpha T_s} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & T_s & \Phi \\ 0 & 0 & 0 & 0 & 1 & \frac{(1 - e^{-\alpha_v T_s})}{\alpha_v} \\ 0 & 0 & 0 & 0 & 0 & e^{-\alpha_v T_s} \end{bmatrix} \tag{6}$$

where $\Phi = (e^{-\alpha_v T_s} + \alpha_v T_s - 1)/\alpha_v^2$, and α_v is a correlation parameter which models different classes of manoeuvring targets. The details of the covariance matrix Q_k of the process noise η_k and other