Research Statement

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1 Research Interests

My research interests span the areas of robotics, mechatronics, and control theory. My interests are based on an interdisciplinary approach including robotic design, modeling, innovative mechatronics, and control strategies. I have a specific interest in robotic systems including flying/ground robots, aerial/ground manipulators, and homogeneous/heterogeneous multi-robot systems. My interests in control strategies include robust, predictive, cooperative, and distributed.

2 Past Work

My Dissertation Research – Novel Quadrotor Manipulation System: During my MSc and Ph.D. works, we propose a novel aerial manipulator that consists of a 2-link manipulator attached to the bottom of a quadrotor. This proposed system enables the end-effector to achieve any arbitrary orientation by increasing its DoF from 4 to 6. Moreover, it provides enough distance between the quadrotor body and the object to be manipulated. System forward kinematics and dynamics considering the effect of carrying a payload are investigated. To define the task objectives in the operational space a point-to-point inverse kinematic algorithm is developed which can only receive a Cartesian point in the task-space and it cannot receive a trajectory to follow.

A customized aerial manipulator is designed and built. Its parameters are identified. Direct relationships between Pulse Width Modulation (PWM) and each of the angular speeds, thrust forces, and drag moments of the rotors are identified. A strategy is developed to estimate the attitude of the quadrotor based on the Inertial Measurement Unit (IMU) measurements. The results of the experiments show a satisfactory accuracy of the identified structure parameters, the identified rotor assembly parameters, and the attitude estimation algorithm. Moreover, the controller of the proposed quadrotor manipulation system is designed based on three control techniques: feedback linearization based PID control, Direct Fuzzy Logic Control (DFLC), and Fuzzy Model Reference Learning Control (FMRLC). These controllers are tested to achieve both the system stability and trajectory tracking under the effect of picking and placing a payload and the effect of changing the operating region.

Meanwhile, the research on aerial manipulation has been increased rapidly. However, the introduced systems suffer from either limited end-effector DoF or small payload capacity. The systems that use a gripper suffer from the limited allowable DoF of the end-effector. The other systems have a manipulator with either two DoF but in a certain topology that disables the end-effector to track arbitrary 6-DoF trajectory or more than two DoF that decreases greatly the possible payload carried by the system. To this end, we still work to complete our proposed aerial manipulator, which still has a unique topology to enable the end-effector to track the 6-DoF trajectory with the minimum possible number of actuators/links and hence, maximize the payload and/or mission time. Experimental implementation of the proposed robot with the development of the measurement and estimation scheme to get the full state vector of the platform are conducted. A novel inverse kinematics algorithm to prove the ability of the system to track arbitrary 6-DoF task space trajectories and facilitates designing the controller in the quadrotor/joint space is proposed. To achieve system robustness, optimize power consumption, and satisfy state constraints, a robust optimal control based on the MPC (Model Predictive Control) and Dob (Disturbance oBserver) approaches is proposed. A robust sensor-less contact force estimation and impedance control are presented.

UAVs Formation Control: As the first step for cooperative manipulation, we study the formation control of a team of quadrotors. In this work, we propose a cooperative formation control strategy with unidirectional network connections between UAVs. Our strategy is to apply a consensus-based algorithm to the UAVs so that they can cooperatively fly in formation. First, we show that UAV models on the horizontal plane and in the vertical direction are expressed as a fourth- and second-order system, respectively. For a network structure composed of bidirectional or unidirectional network connections under the assumption that the network has a directed spanning tree, we provide conditions for formation control gains by using the generalized Routh stability criterion such that the UAVs can asymptotically converge to the positions for the desired formation. The proposed control algorithms are validated through simulations and experiments.

3 Current Work – Car-like Vehicles Platooning in an Urban Environment

Shared transportation systems in urban environments are the current trend to overcome transportation problems toward an eco-friendly city. One of the recent trends is using a car-sharing system. However, one of the main problems of the car-sharing system is related to the relocation/redistribution strategies such that the cars are always available and well distributed in all stations which require more sophisticated techniques to be implemented in cities. An alternative, the VALET project proposes a novel approach for solving car-sharing vehicles redistribution problem using vehicle platoons guided by professional drivers who come to pick up and drop off vehicles over the stations.

The difference between the platoon motion in an urban environment and that in the highway environment is twofold. First, in the highway environment, a Cartesian frame is often used to describe the platoon motion in order to facilitate the manipulation of geometric transformations. However, in urban environments, for vehicle control, the motion has to be represented with respect to a path that the vehicle intends to follow. Thus, the Curvilinear/path coordinates are used instead to represent the vehicle motion. Second, unlike the highway environment, the vehicle traveling in an urban environment has to change its speed to consider the environment properties such as bumps, curvature, etc. Thus, it is not practical to assume that the leader vehicle is moving with constant velocity as it is assumed in the highway applications.

The framework of the longitudinal platoon control consists of four components, including Vehicle Dynamics, Information Flow Topology (IFT), Distributed Controller, and Spacing Policy. The vehicle longitudinal dynamics are inherently nonlinear.

New Platoon Model: For vehicle dynamics, different models are used in the literature, including linear and nonlinear models. Three linear models are frequently used includes a single integrator, double integrator, and third order. To the best of our knowledge, despite the huge amount of relevant literature to date, few studies in the literature have handled the problem of platooning in the urban environment/path coordinates. In these studies, the authors assume a first-order model for vehicle dynamics which has many defects. Therefore, in our research, a third-order longitudinal dynamic model is used and its corresponding one in the path coordinates is proposed such that one can design a controller to achieve control objectives in the path (operational) coordinates explicitly.

Longitudinal Control Considering Limited Communication Capabilities: For the distributed control, three main control objectives are required. First, the platoon can navigate in an urban environment (curvilinear path). Second, achieving position and velocity tracking for the follower vehicles inside the platoon considering that the leader is either autonomous or manually driven and it may move with variable velocity. Third, guarantee the string stability, i.e., the error signals will attenuate when propagating downstream the vehicle string. The string instability may result in a rear-end collision. In the literature, many platoon controllers are proposed. The simplest platoon controller is called Adaptive Cruise Control (ACC). Recently, platoon control is based on a distributed controller known as Cooperative Adaptive Cruise Control (CACC). The concept of the CACC is the same as ACC, except that in CACC, the vehicles use a communication system to share information with their neighbors to improve the whole system's functionalities and performance. There are six main approaches in designing a platoon controller, including Linear, Optimal, $\mathcal{H}_\infty$-based, Sliding Mode, Model predictive, and Consensus-based controller. However, none of these works consider the control in the path coordinates. Moreover, they assume that the leader travels with a constant velocity that is not applicable to platooning in an urban environment in which the leader is driven by a human. Therefore, in our study, the authors propose a controller that can achieve asymptotic stability of the tracking errors and the platoon string stability as well, even if the leader travels with variable velocity.

Several spacing policies are proposed in the literature. The constant distance spacing policy is used commonly in the literature due to its capability to achieve a high traffic capacity. However, to achieve string stability, more communication links are required to transmit information the leading vehicles to all the vehicles in the platoon. The Information Flow Topology represents the inter-vehicle communication topology that the vehicles can utilize to acquire the information from its surrounding vehicles. Thanks to the rapid advancement of vehicle-to-vehicle (V2V) communication technology, various IFTs are developed, including Predecessor Following (PF), Predecessor-Leader Following (PLF), Bidirectional (BD), etc. The PLF topology is commonly used in the literature in which the leader communicates with all the vehicles in broadcast, and every other vehicle also considers information from its predecessor to compute the control action. However, for a low-cost onboard communication module that has limited bandwidth capabilities or for robust communication, high-speed two-channel communication is not feasible/preferred. Therefore, in this study, the proposed control law is designed depending on a hybrid PLF topology. That is, the leader broadcasts its information (position, velocity, and acceleration) to all the vehicles via a communication-based link. For the inter-followers communication, the inter-vehicle distance is measured by a distance sensor, e.g., laser, i.e., by a sensor-based link. Furthermore, the proposed control law does not require the predecessor velocity. In addition, in our study, the proposed control strategy combines platoon maintaining, gap closure, and collision avoidance functionality into a unified control law. For platoon creation, the gap closure scenario is highly recommended for achieving a fast convergence of the platoon. For that, an algorithm is proposed to adjust the controller parameters online. The platoon longitudinal controller is supported by a collision avoidance capability so that a safe inter-vehicle distance, in case of an abnormal situation, occurs such as sudden braking of a vehicle inside the platoon, can be guaranteed. The collision avoidance is based on the potential filed technique in which we use a potential function that has smooth and local effects during the transitions.

The whole control system is analyzed, then under the effect of communication delay and actuator dynamics, conditions for both internal and string stability are provided. Finally, studies are conducted to demonstrate and validate the efficiency of the presented framework in both simulation and real-time. For a more realistic simulation setup, the controller is tested by implementing of the car-like vehicles platoon in a vehicular mobility simulator called ICARS, which considers the real vehicle dynamics and other platooning staff in urban environments. Verification in practice is enlightened by experiments performed with car-like vehicles. The demonstration is successfully conducted in the campus of the Ecole Centrale de Nantes, Nantes, France.

A New Observer-based Longitudinal Control: It is well known that the usage of the velocity of the predecessor in the control law results in both a smother vehicle acceleration, and hence more comfortability and fuel saving, and faster converse of the platoon. Therefore, we propose an observer-based control law in which an observer is used to estimate the predecessor vehicle based on the position information received via the sensor link. Consequently, the control law utilizes both the leader information via a communication-based link, the predecessor position via a sensor-based link, and the predecessor velocity via an observer without a need to communicate with the predecessor. Moreover, internal stability and string stability are analyzed.

Heterogeneous Platoon, Low-level Controller Deficiency, and Time Delay Compensation: During the analysis of the aforementioned control algorithms, we assume the platoon are homogeneous, i.e., the vehicle has identical kinematics, dynamics, and actuator constraints, particularly when we study the string stability. In addition, we assume that the vehicles have ideal linear models, and the low-level controller works perfectly. In practice, it is common that these assumptions can be violated and bring the platoon to both internal and string instability. Furthermore, we consider the time delay problem induced due to the communication among the vehicle in the platoon in which the condition on the maximum time delay is provided to guarantee both the internal and string stability. Therefore, we are working on the control scheme to compensate for that delay. Few studies in the literature are conducted to compensate for the time delay. However, they have not tackled it in the framework of platoon control in which the control and compensation scheme must fulfill the string stability requirement. Most of these issues are not tackled in the literature, thus we are working to propose a new control scheme to address them.

4 Future Research Directions - Heterogeneous Cooperative Manipulation Systems

Cooperative Aerial – Ground Manipulators: Recently, several studies are proposed to solve the limited payload and flight problems associated with aerial manipulation based on the cooperation of multiple Aerial Manipulators (AMs) for construction and large load handling. However, these approaches still suffer from small payload capacity and endurance issues. On the other hand, Ground Manipulators (GMs) have larger payload capacity and longer endurance time but suffer from limited joint torques and a small workspace, reducing their manipulation capabilities particularly for long objects. We can overcome the limitations of previous approaches by exploiting the combined advantages of both AMs and GMs. The small payloads of AMs are compensated for by the strength of the GMs, whereas the limited workspace and poor Cartesian torque at the GM end-effector are balanced by the unlimited workspace and the favorable lever provided by AMS. This system can solve problems in the material/object handling inside the Warehouses and Agricultural sectors. For these heterogeneous cooperation manipulation system, several problems are not handled includes control-aware motion planning scheme, heterogeneous end-effector DoF, mixed actuator constraints, load distribution for different payload capacities, Optimal utilization of the redundancy of the overall heterogeneous system during cooperative manipulation, manipulation team reconfiguration, force estimation, etc.

Similar studies have to be conducted for the cooperation between the aerial manipulators and the under-water manipulators which can be widely used in the rescue operation in the sea.

Human-Aerial Manipulators Cooperative Manipulation: Research in Aerial Manipulators (AMs) has been increased rapidly in recent years due to its superior mobility over Ground Manipulators (GMs). However, two main challenges are associated with AMs which are payload capacity and endurance time limitations. in this research program, a solution is proposed to tackled these limitations by enabling a human, who has larger payload capability compared to small AMs, to cooperatively handle large objects and guide the motion of the object from a starting point to a destination point. Human-AMs cooperative manipulation problem is not tackled in the literature. Hence, some research challenges arise and have to be addressed such as estimation of unknown object parameters. All the techniques in the literature are dedicated to the human-GMs cooperation that depends on the sensor-based measurement of force/torque. However, AMs are hard to equip by this heavy sensor. Moreover, the study of the integration between a robust adaptive control algorithm and an estimation algorithm has to done to improve both stability and performance. This work can be extended to include multiple AMs and GMs to enhance the manipulation performance by completing the capabilities owned by each agent (i.e., human, AM, and GM). The development of such a system has a great effect on the enhancement of material/object handling in several vital places such as automated warehouses which leads to higher productivity.