Dr Hedengren -

Following is a manuscript for our report on estimating the mass of a UAV. Interest in automating agricultural tasks using UAVs has increased as they have become more robust and reliable in recent years. One potential application is for UAVs to monitor crop health and administer pesticide. If the pesticide is all stored on board the UAV, then it's mass will change as it dispenses the pesticide. This significantly affects flight dynamics and little, if any, research has been published on estimating mass and adapting control accordingly. Significant contributions include:

- Estimating unchanging mass value of a UAV
- Estimating unchanging flow rate of pesticide dispensed by UAV

Thank you,

Jon Terry

Estimating the Changing Mass of an Unmanned Aerial Vehicle

Jon Terry, Jacob Barzee

Introduction

Agricultural activity has been increasingly automated in recent years, which increases efficiency and reduces cost for farmers. Most of this automation has taken place with land vehicles, but improvements in flight controls have made UAVs sufficiently robust to be useful in the agricultural industry as well. One potential use for UAVs is monitoring crop health and distributing pesticide accordingly. Presently, pesticide is distributed generally instead of as needed. If a UAV could monitor crop health and administer pesticide as needed, resources would be saved and crops would not be given excessive amount of pesticide as a matter of course. Two potential platforms for accomplishing pesticide distribution via UAV include 1) a UAV flies with all pesticide on board or 2) UAV is tethered to a land vehicle, which supplies pesticide to the UAV for distribution. In this work, we focus on the first platform.

Typically, when controlling a UAVs flight, the mass of the UAV is typically known and unchanging. Here we present a control and estimation structure for a UAV with pesticide on board, which flows out of the UAV at constant rate.

Literature Review

Sun et al., in [1] and [3], describes a system where a mothership takes a pseudo circular path optimized to hold a drogue at the end of a cable as close to motionless as possible for recovery of smaller drones. The second article validates a model for towed cable systems represented by a lumped mass extensible cable. The cable is simulated as an elastic string with mass points on connections. Equations of motion on the jth cable joint and the drouge are given by

$$m_j \ddot{p}_j = T_j + G_j + F_j^{aero} - T_{j+1},\, j = 1,2,\ldots,N-1$$

$$(m_N + m_{dr})\, \ddot{p}_N = T_N + G_N + F_N^{aero} + G_{dr} + F_{dr}^{aero}$$

S. M. Safdarnejad et al., in [2], explore options for finding an initialization to optimize solving time for models. Two simple options exist for initialization:

1. Simplify the model and solve
2. Break down model and solve for subsets of variables

The article examines a system consisting of a UAV tethered to a ground vehicle. The simulation and its possible difficulties are reviewed: “Unique aspects of this example problem for DAE initialization are that it is an unstable system, highly nonlinear, and has many decision variables. The optimizers plan a path for the UAV by adjusting the acceleration of the UAV in north, east, and vertical directions.” Methods for this initialization specifically are:

1. lower block triangular solution

2. single simulation with no degrees of freedom

In summary, complex dynamics of a tethered UAV have been optimized for various scenarios. As far as we could ascertain, no work on modeling or estimating a UAV of changing mass has been attempted until now.

Methods

The APMonitor modeling language was used for simulation, control and estimation in this work. Estimation was the focus of the work, and so the UAV model has been simplified as much as possible. The UAV is treated as a point mass, and takes 3 degree of freedom force (from the rotors) as the manipulated variable for the controller. Force effects position by $F=ma$ where a is the second derivative of position. Wind velocity is also taken into consideration (as a constant in this model), and is assumed to be additive to the velocity provided from the rotor force. However, a more accurate simulation would treat wind as a disturbance force that varies with time.

Simulation

In this work, a simple quadrotor UAV is used. This simplifies the model because it can be assumed that the UAV can readily apply force in each direction (unlike a fixed-wing aircraft, which has much more complex dynamics). The controller's objective is to follow a pre-set path (identified as “pipeline” in the following figures) at a set altitude. The controller manipulates force in each direction (up, north, and east) to control for position. Figure 1 below demonstrates this objective. The UAV starts at position (0,0,30), moves to begin following the pipe, and then accurately maintains north/east position over the pipe.

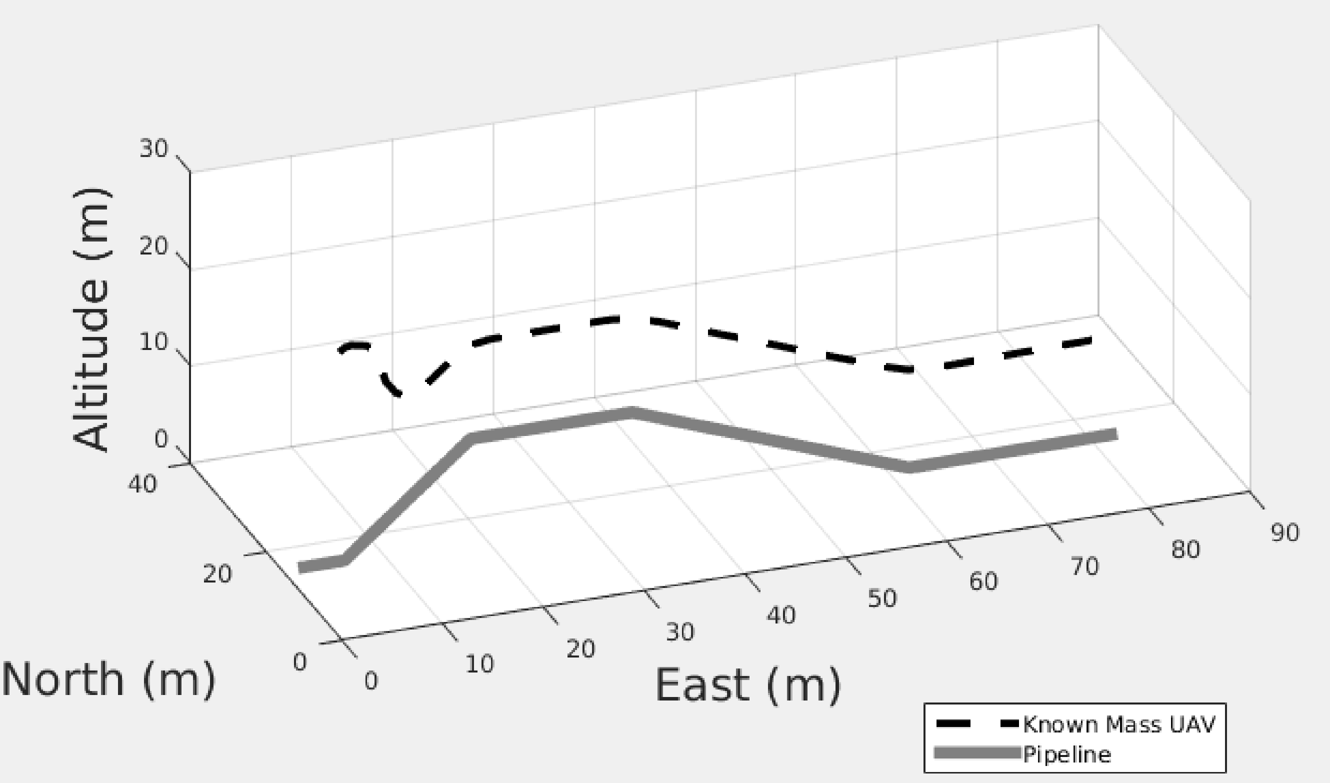

Figure 1 Flight path of UAV, tracking pipeline

A sensitivity analysis was performed to better understand the relationship between mass and position. This is necessary to ensure that the mass parameter is observable or, in other words, that the estimator will be able to gather enough data during the course of the current target trajectory to be able to sufficiently estimate the mass of the UAV. The analysis shows changing the mass by 1 kg would effect an average change of 72.6 m in each direction (up, north, and east), which indicates that our control variables (position) are quite sensitive to mass.

Sensitivity between force and position was also analyzed. The force applied directly affects acceleration in each direction (up, north, and east), which of course affects the position. The analysis shows changing the force by 1 N would effect a change of 0.4 m in each direction, which indicates that our control variables (position) are quite sensitive to force, as expected.

A d-optimality process was under consideration, which would help determine the best flight path or UAV movements for efficiently determining the mass. The current path is not likely to be the most efficient, but it is sufficient for determining flow rate. If the flow rate itself were to vary, then a more efficient path would likely be necessary.

Estimation

To begin, an estimator was been designed to predict a constant mass value. Simulation was first run, recording force and position data with time. Estimation was then run on the same model using the output simulation data. Figure 2 compares the flight paths of the simulation with and without the estimator. The real mass of the UAV was set to 0.400 kg, and the estimator's predicted value agreed to within 6 significant figures. The noise in the “measured” data introduces an overall bias, hence the offset between the two flight paths.

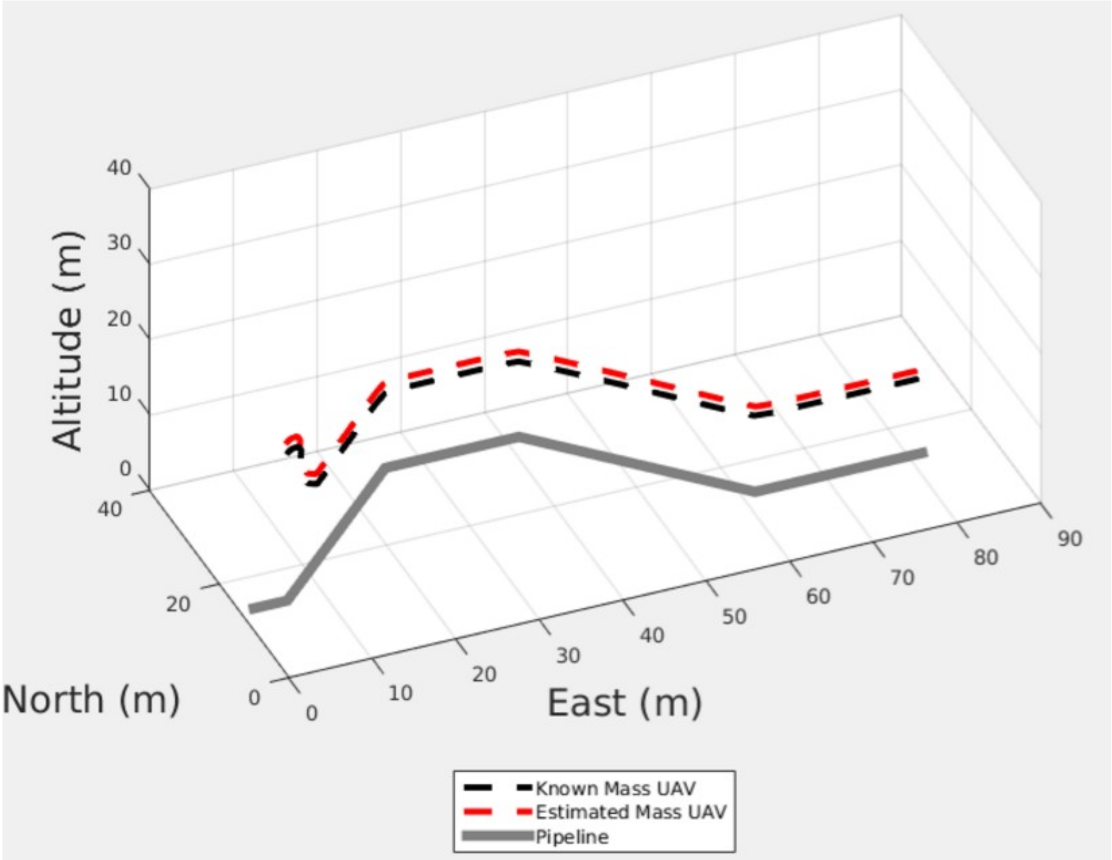

Figure 2 Flight path of simulated UAV (black) and flight path with estimated mass (red)

The next step was to introduce changing mass (according to a constant flow rate) to the model, and estimate the flow rate. The UAV's initial mass was set to 10 kg and the flow rate to 0.1 kg/s. The estimator, using the same process as described for estimating a constant mass value, successfully predicted the flow rate to within 6 significant figures. Figure 3 shows the results of the estimation, similar to above.

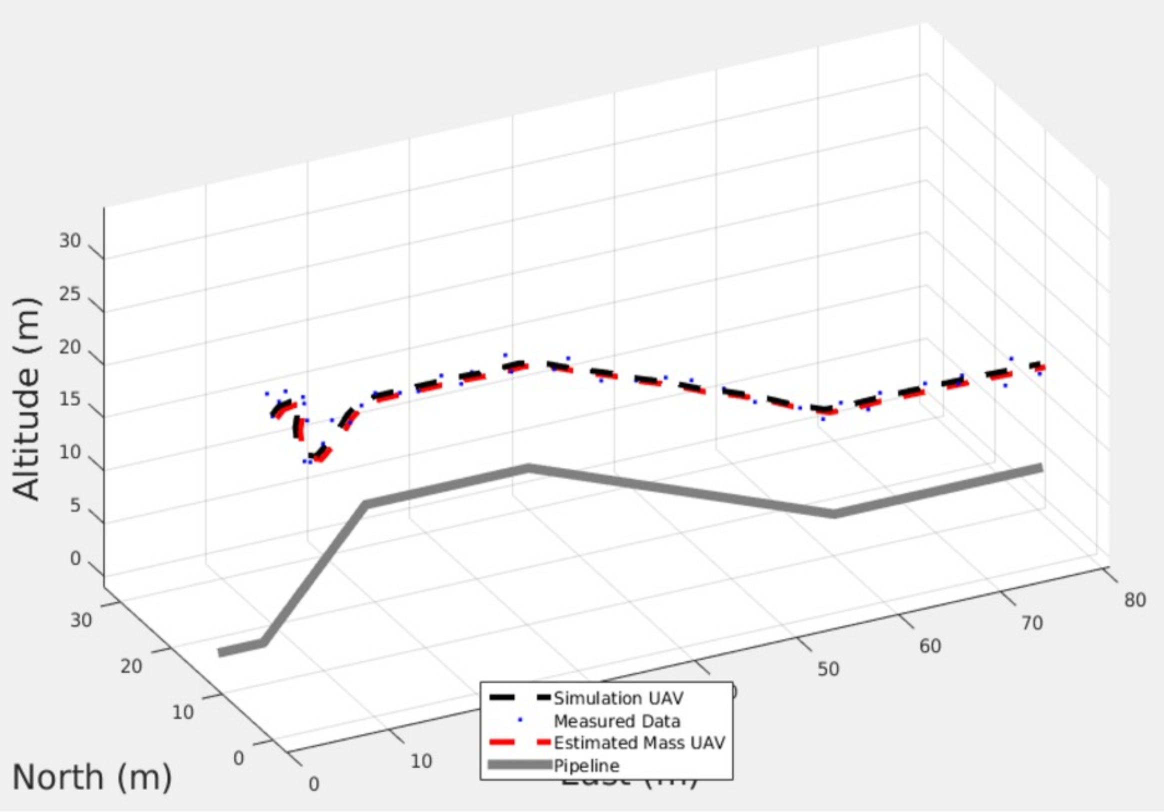

Figure 3 Flight path of simulated UAV (black) and flight path with estimated flow rate (red)

Discussion

This work provides a useful step in utilizing UAVs for agricultural tasks, but much work is still needed in this area before UAVs can be useful for pesticide distribution. The work in this paper assumes a constant pesticide flow rate, which may be accurate for short time periods, but not for a full flight. Additionally, the pesticide would spray out of a nozzle on the UAV, which may introduce flight dynamics that would need to be taken into consideration in the model.

In this paper the UAV follows a pre-defined path. Autonomous path planning in real time for pesticide distribution would be greatly beneficial, especially if combined with a vision component to determine where pesticide is needed. The path to get the UAV from a launch station to the effected area is straightforward, but the more interesting work involves planning the path the UAV takes while distributing the pesticide (assuming the area is relatively large when compared to the UAV).

Additionally, it would be useful to tether the UAV to a land vehicle, which would supply resources to the UAV such as power (to increase flight duration) and/or pesticide. If pesticide were being supplied via tether then the mass of the UAV would not change. This component of the problem has received some attention in the literature, but could be combined with path planning to achieve greater applicability to an agricultural application.

Lastly, we have assumed a quadrotor UAV in our work. Implementing the complex dynamics of a fixed-wing aircraft for any of the work mentioned above should provide interesting and useful results.

Conclusion

In this work, we have demonstrated a method for predicting the mass of a UAV in flight, using only force and position data from simulation. UAV mass and pesticide flow rate values was accurately estimated to within six significant figures.

References

1. Sun, L., Castagno, J., Hedengren, J. D., and Beard, R. W., Parameter Estimation for Towed Cable Systems Using Moving Horizon Estimation, IEEE Transactions on Aerospace and Electronic Systems, Vol. 51, No. 2, April 2015.
2. Safdarnejad, S.M., Hedengren, J.D., Lewis, N.R., Haseltine, E., Initialization Strategies for Optimization of Dynamic Systems, Computers and Chemical Engineering, 2015, Vol. 78, pp. 39-50
3. Sun, L., Hedengren, J. D., and Beard, R. W., Optimal Trajectory Generation using Model Predictive Control for Aerially Towed Cable Systems, Journal of Guidance, Control, and Dynamics, Vol. 37, Issue 2, pp. 525-539, 2014.