SIMULATION MODELING AND DYNAMICS OF ROTORCRAFT-BASED UAS

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14. ABSTRACT
The University of Maryland Rotorcraft Flight Dynamics Simulation HeliUM is extended to model electric propulsion systems for rotorcraft-based multirotor UAS. Each rotor can be controlled by a user-defined mix of RPM and swashplate controls. HeliUM computes the trim state, the time marching response to arbitrary pilot inputs, and extracts high-order state-space linearized models suitable for flight dynamics and control analyses. The solutions do not require that rotor speeds be constant and identical across all rotors, and a common 1/rev frequency is not required. The model is validated using test data for the TRV-80 UAS configuration, which is a smaller version with the same rotor arrangement and overall geometry of the TRV-150C Tactical Resupply Unmanned Aircraft System (TRUAS). The engineering simulation HeliUM can model rotorcraft-based UAS of any size, Groups 1 to 5.

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1 Background, Motivation, and Objectives

The research conducted in the present project addressed the technical area of Aeromechanics, and focused on rotorcraft-based, multi-rotor, Unmanned Aircraft Systems (UAS). Many such UAS are of relatively small size, and are developed mostly under a "build and test" approach. As a consequence, the physics-based engineering simulation models currently available tend to lag in sophistication and accuracy behind those for full-size rotorcraft. Furthermore, the fundamental understanding of the flight dynamics and control of these UAS still shows many gaps, and the very concept of handling qualities is evolving. UAS engineering simulations have to be easy to set up, because new configurations can be produced quickly, but at the same time have to be sophisticated enough to capture the sometimes complex physics of these aircraft.

The initial objectives of the proposed research were:

1. To develop physics-based engineering simulation models for hybrid multirotor UAS capable of both rotor- and wing-borne flight;

2. To develop methodologies for a preliminary assessment of UAS handling qualities through desktop computer simulations; and

3. To improve the fundamental understanding of the behavior of multirotor UAS in maneuvers and missions typical of the maritime environment such as ship deck landing.

Not all activities planned to achieve the objectives above were completed. The activities actually completed are described in the sections below.

2 `HeliUM` flight dynamic simulation model

The activities under the present project were part of the continued development of `HeliUM`, the University of Maryland Flight Dynamics Simulation Model. `HeliUM` contains the implementation of over ten doctoral dissertations, and has focused on the fundamental aspects of the modeling of various rotorcraft configurations [1]. Starting from 2019, the research focused on the specific aspects of the flight dynamics and control modeling of multi-rotor UAS, under a U.S. Army DEVCOM research grant. This included extensions needed to model an arbitrary number of rotors, in arbitrary positions and orientation, and controlled with any desired combination of rotor speed and swashplate controls.

The activities under the present project were supposed to further extend the simulation with state-space ODE models of electric propulsion system, and of flexible wings of user-defined number, geometry, and location on the aircraft.

The aircraft used in the development was the Malloy TRV-80, shown in Fig. 1. The TRV-80 is a smaller version, with the same rotor arrangement and the same general geometry, of the TRV-150C Tactical Resupply Unmanned Aircraft System (TRUAS), shown in Fig. 2.

Figure 1: Malloy TRV-80.

Figure 2: Malloy TRV-150C Tactical Resupply Unmanned Aircraft System (TRUAS).

3 Modeling of electric motors

The model of an electric motor was added to `HeliUM`. The mathematical model is taken from Malpica and Withrow-Maser [4], and consists of the following coupled motor-rotor mechanical equation:

$$\frac{d\Omega}{dt} = -\left[-\frac{cK_e^2 r^2}{R_a}\Omega + Q_A - Br^2\Omega + \frac{cK_e r}{R_a}V_a\right]\frac{1}{I_r + Jr^2} \tag{1}$$

where: B is a linear representation of mechanical friction or viscous losses in the drive system, c is the conversion factor between SI and British units (e.g., 0.7374 lb-ft/Nm), I_r is the rotor inertia, J is the inertia of the high-speed drive components (motor and coupled transmission components), K_e is the back-EMF constant, Q_A is the rotor aerodynamic torque, r is the drive system gear ratio, such that the total angular momentum is $(I_r + Jr^2)$, R_a is the equivalent resistance, V_a is the voltage applied at the armature, and Ω is the rotor speed.

This is an elementary model, but it is excellent for an initial software implementation that can be easily extended to more sophisticated and realistic models. The current `HeliUM` set up has already provisions for multiple motor models, different installation parameters, arbitrary rotor/motor matches, and it is extendable to other types of motor. Each rotor can be controlled by a user-defined mix of RPM and swashplate controls.

The introduction of a propulsion system state-space model makes the rotor speed Ω a state, and it is useful to summarize the mathematical treatment in HeliUM of rotor speed depending on the type of modeling selected.

3.1 Constant rotor speed (single rotor) and identical for all rotors (multirotor)

In this case, for a single main rotor configuration, the rotor speed Ω is constant. For multirotor configurations, such as the UAS of the present study, the rotor speeds $\Omega_i, i = 1, \ldots, N$ are both constant and identical in magnitude (i.e., the directions of rotation may differ) across all the N rotors. Then, a common period of rotation or, equivalently, a 1/rev frequency, exists. Time t and azimuth angle ψ are related by $\psi = \Omega t + \psi_0$, and therefore t and ψ are essentially interchangeable. The specific value of ψ_0 is often not important (except for multirotor configurations, when the relative phasing among the rotors could be important), in which case it can usually be simply set $\psi_0 = 0$.

In this case, the solution algorithms for trim, linearization, and time integration are valid in their basic form [1], and no changes are necessary.

3.2 Variable or nonuniform rotor speed—Ω is a control

In this case, for a single main rotor configuration, the rotor speed Ω is not necessarily constant. For multirotor configurations, the rotor speeds $\Omega_i, i = 1, \ldots, N$, can be:

- variable for one or more rotors; and/or
- constant but not identical in magnitude across the N rotors.

For multirotor configurations, the differences in rotor speed are considered only across the rotors that are described by individual blade models. Rotors that are described as solid disks that generate forces and moments are not included. For example, a single main rotor configuration, with a main rotor modeled with individual blades, and a tail rotor modeled as a solid disk and rotating at a speed that is constant, but different from that of the main rotor, will be treated as a constant rotor speed case.

In this case, a common period of rotation or, equivalently, a 1/rev frequency, no longer exists. The relationship between time t and azimuth angle ψ_i is now $\psi_i = \Omega_i t + \psi_{0i}$, i.e., it varies depending on the rotor, and therefore t and ψ are no longer interchangeable at the complete aircraft level. The basic solution algorithms for trim, linearization, and time integration are modified compared with their basic form to account for the lack of a common period.

Rotor speed is provided as input (constant or time-varying) or is set by the trim procedure. In this case, `HeliUM` builds the rotor speed[1] Ω from the pilot inputs δ based on a user-defined mixer matrix (and a bias vector, not shown). Therefore Ω is algebraically (i.e., with no time derivatives) related to the pilot inputs, schematically indicated as $\Omega = k\delta$, and can be considered as a control, as shown in Fig. 3.

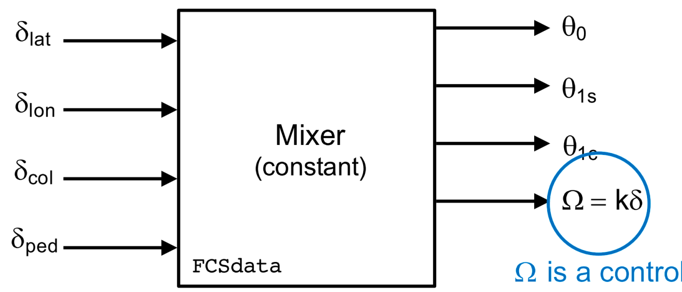

Figure 3: HeliUM treatment of rotor speed Ω—No propulsion system model.

Because of the lack of a common 1/rev frequency, both the trim algorithm and the linearization procedure are modified, and depend on the specific values of Ω.

One additional ODE must be written for each of the N rotors, and the resulting set of N ODEs must be appended to the rest of the model:

$$\Omega_i(t) = \dot{\psi}_i(t) \qquad \text{with } \psi_i = \psi_{0i} \text{ at } t = t_0 \qquad i = 1, 2, \ldots, N \tag{2}$$

where $\psi_i(t)$ is the azimuth angle of the reference blade of the i-th rotor. The specific values of the azimuth angles of each rotor are generally not important, but the *relative* values across rotors can be.

Equation (2) can be rewritten in implicit, vector form, as:

$$\mathbf{f}_{\boldsymbol{\Omega}}\left(\dot{\mathbf{x}}_{\boldsymbol{\Omega}}; t\right) = \left\{\dot{\mathbf{x}}_{\boldsymbol{\Omega}}(t) - \boldsymbol{\Omega}(t)\right\} = \mathbf{0} \tag{3}$$

where $\mathbf{x}_{\boldsymbol{\Omega}}$ is the portion of the state vector $\mathbf{x}$ of the complete aircraft model that contains the reference blade azimuth angles $\psi_i(t)$. The dimension of all the vectors is equal to the number of rotors.

In this case, there is no propulsion system model, and therefore the mechanism through which the rotor speed can change with time is through pilot inputs. For multirotor configurations, dissimilar but constant rotor speeds can also be prescribed as inputs. This

[1]Note that rotor speed in this section is indicated by Ω, but typically `HeliUM` uses Ω^2 instead of Ω.

arrangement is shown schematically in Fig. 3 for one rotor. Rotor speed Ω is obtained from a linear combination of pilot stick and pedal inputs δ, i.e., it is algebraically linked to δ (this is symbolically indicated in the figure as $\Omega = k\delta$), and in this sense Ω is a control.

In the current version of `HeliUM`, rotor speed Ω is an *open loop* control, i.e., there are no feedback loops that contribute directly to Ω. The only partial, and limited, exception, is that `HeliUM` contains a simple stability augmentation system model in which body states are fed back to stick and pedal inputs δ. If one or more of the δ control rotor speed, then a simple feedback loop ends up being established.

If the rotor speed equations, Eqs. (3), are included in the model, they need to be considered only for time integration solutions of the equations and for the extraction of linearized dynamic models. They can be omitted for trim calculations because, in this case, rotor speed ends up being prescribed as part of the solution algorithm.

3.3 Variable or nonuniform rotor speed—Ω is a state

This situation is similar to that of the previous section, except that the mathematical model includes one or more ODEs for the propulsion system. This is the extension of the model specifically developed as part of the present project. In this case, the pilot stick and pedal inputs δ are not converted directly to rotor speed, but generate inputs to a propulsion system ODE model, as described schematically in Fig. 4. The fact that the propulsion system is described by one or more ODEs, and therefore introduces its own dynamics, is indicated schematically in the figure by the transfer function $H(s)$. A common rotational period (or 1/rev frequency) again no longer exists. The user can now choose to provide directly the rotor speed Ω as input (constant or time-varying) and/or have it set by the trim procedure, as shown in the previous section, or also to provide it indirectly, as an input $V(t)$ (e.g., voltage or current) to an electric motor model such as that of Eq. (1). The user expresses this choice through an extended mixer matrix (and corresponding extended bias vector, not shown), as shown in Fig. 4.

If the user chooses to link the pilot controls δ to inputs to a propulsion system, symbolically indicated as V, then V becomes a control and Ω becomes a state.

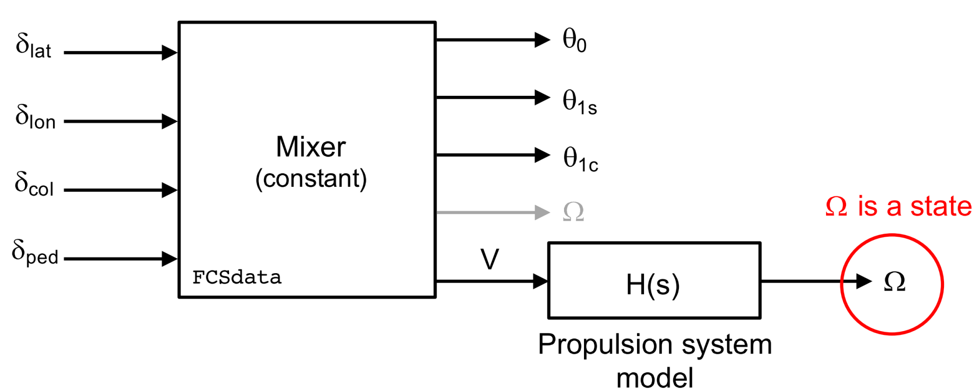

Figure 4: `HeliUM` treatment of rotor speed Ω—With propulsion system model.

Again, because of the lack of a common 1/rev frequency, both the trim algorithm and the linearization procedure are modified, and depend on the specific values of Ω. Figure 4 shows schematically the implementation for one rotor. In `HeliUM`, the options of Fig. 4 can be selected individually for N rotors, plus additional aircraft effectors such as ailerons, rudder, pylon angles, etc. This is done through an appropriate mixer matrix and bias vector, as shown in Fig. 5.

As in the previous section, additional ODEs must be written for each of the N rotors, and the resulting set of ODEs must be appended to the rest of the model to allow the conversion from the baseline time clock to a blade azimuth angle clock. The specific number and type of additional equations will depend on the propulsion system model. In general it will be, for each rotor:

$$\begin{cases} \Omega_i(t) = \dot{\psi}_i(t) \\ \dot{\Omega}_i(t) = \text{propulsion system model} \end{cases} \qquad \text{with } \psi_i = \psi_{0i} \text{ at } t = t_0 \qquad i = 1, 2, \ldots, N \tag{4}$$

where $\psi_i(t)$ is the azimuth angle of the reference blade of the i-th rotor. For example, $\dot{\Omega}_i(t)$ could be given by Eq. (1), page 3. In this case, $\Omega_i(t)$ becomes a state, and can no longer be controlled directly, or "algebraically" from the pilot inputs. In `HeliUM` it is possible, for multirotor configurations, to mix treatments of Ω_i as states or controls for different rotors.

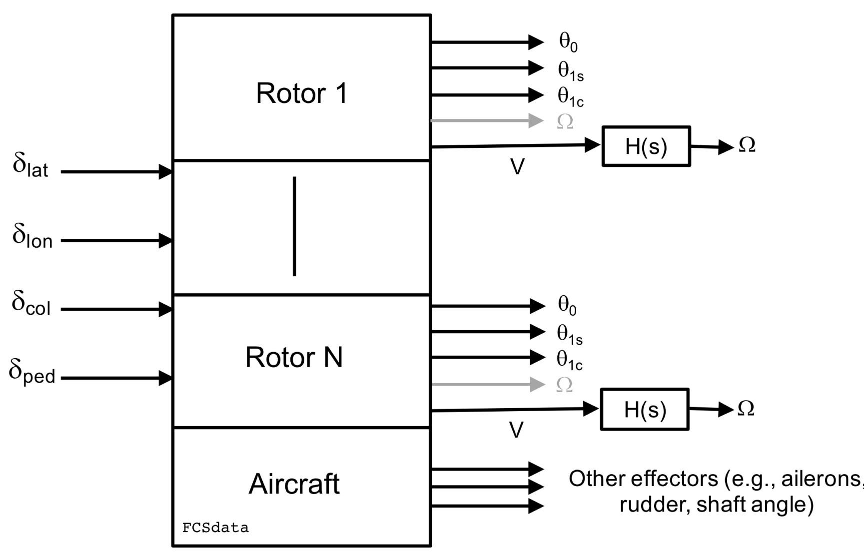

Figure 5: `HeliUM` treatment of rotor speed Ω—With propulsion system model, multiple rotors and other aircraft control effectors.

Therefore, the portions of the state vector for the entire aircraft associated with propulsion systems and rotor speeds are:

$$\mathbf{x}_{PS} = \begin{Bmatrix} \Omega_1 \\ \Omega_2 \\ \vdots \\ \Omega_{N_{PS}} \end{Bmatrix}$$

$$\mathbf{x}_{RS} = \left\{ \begin{array}{c} \psi_1 \\ \psi_2 \\ \vdots \\ \psi_{NR} \end{array} \right\} \tag{5}$$

where NR is the number of rotors. Note that the two portions are not written as a single state vector because they are handled in different places in the software implementation. However, the two portions are clearly related, and this must be taken into account especially when extracting linearized models. As a simple example, consider just the rotor speed and propulsion system ODEs for a 2-rotor configurations, in which rotor 1 has rotational speed Ω_1 controlled directly from the pilot input, and rotor 2 has rotational speed Ω_2 given by a propulsion system ODE model, as in Eq. (4). The equations will be:

$$\dot{\Omega}_2 + a\Omega_2 - Q_2 = 0 \tag{6}$$

$$\dot{\psi}_1 - \Omega_1 = 0 \tag{7}$$

$$\dot{\psi}_2 - \Omega_2 = 0 \tag{8}$$

where Q_2 contains the torque available and the torque required: it is generally a nonlinear function of all the states and controls, but for convenience, and just in this simple example, it will considered constant. In trimmed conditions, as appropriate for the extraction of a linearized model, the rotor speed Ω_1 would be constant and equal to its trim value $\Omega_{1_{trim}}$. Therefore, the equations can be written in matrix form as:

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \left\{ \begin{array}{c} \dot{\Omega}_2 \\ \dot{\psi}_1 \\ \dot{\psi}_2 \end{array} \right\} + \begin{bmatrix} a & 0 & 0 \\ 0 & 0 & 0 \\ -1 & 0 & 0 \end{bmatrix} \left\{ \begin{array}{c} \Omega_2 \\ \psi_1 \\ \psi_2 \end{array} \right\} + \left\{ \begin{array}{c} -Q_2 \\ -\Omega_{1_{trim}} \\ 0 \end{array} \right\} = \left\{ \begin{array}{c} 0 \\ 0 \\ 0 \end{array} \right\} \tag{9}$$

The main, rotor speed-related portions of the trim algorithm for the variable or dissimilar rotor speed case, are summarized in Fig. 6.

The different roles, and corresponding treatment, of blade azimuth ψ and rotor speed Ω, with and without a propulsion system model are especially important for the time integration of the equation of motion and the conversion from time to azimuth clocks and back. They are summarized in Fig. 7.

4 Sample Validation Results

Figure 8 shows `HeliUM` trim results with the motor model of Eq. (1). The actual motor parameters for the TRV-80 were not available. Therefore, notional motor parameters were selected so that the trim rotor speed would be exactly 2500 RPM to enable a precise comparison with previous validation data. The C_T/σ curves in the figure refer to one of the eight rotors of the TRV-80 (data from Ref. [3]), on a hover test stand:

1. *BEMT VFS Paper*: predictions from a Blade Element-Momentum Theory (BEMT) model, from Ref. [2].

2. *Test*: the experimental values, also from Ref. [2].

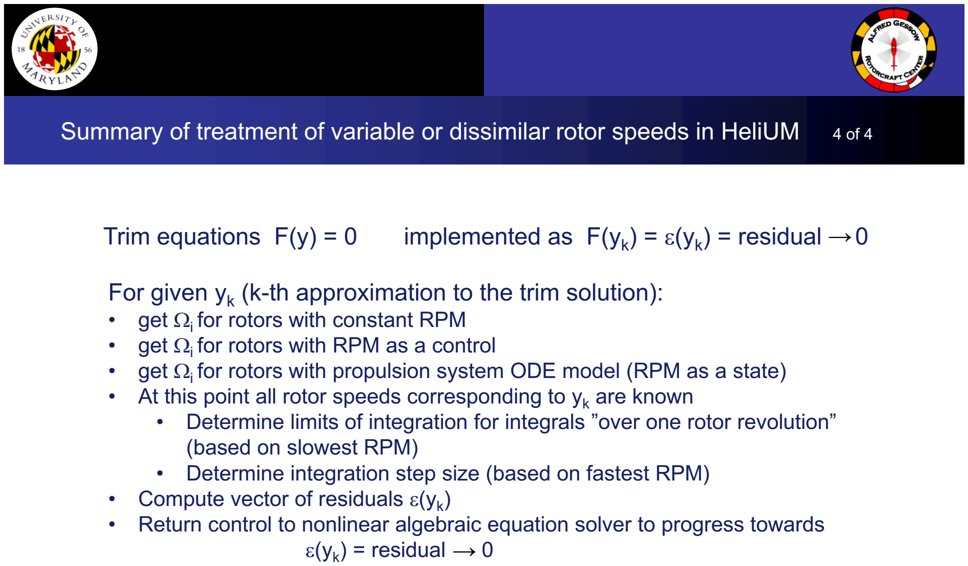

Figure 6: Summary of HeliUM trim algorithm with variable or dissimilar rotor speeds.

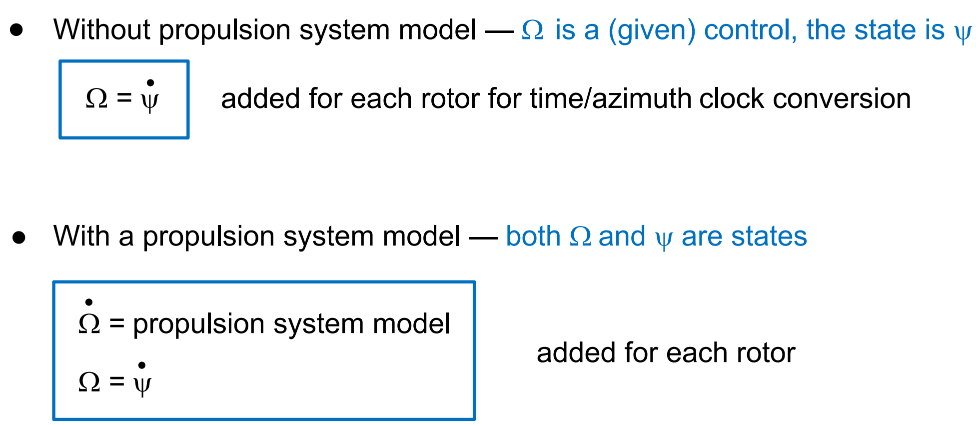

Figure 7: Summary of HeliUM treatment of blade azimuth ψ and rotor speed Ω with and without a propulsion system model.

3. *HeliUM*: the predictions of a previous version of HeliUM, without propulsion system modeling.

4. *HeliUM with motor modeling*: the prediction of the improved version of HeliUM, developed as part of the present project, with the new propulsion system model.

Figure 9 again shows HeliUM results with the motor model of Eq. (1) for one of the eight TRV-80 rotors. The figure shows the time history of rotor RPM in response to a step input of voltage V. The curve marked "*Digitized from VFS paper*" shows the experimental results obtained on the hover test stand, digitized from one of the figures of Ref. [2]. The

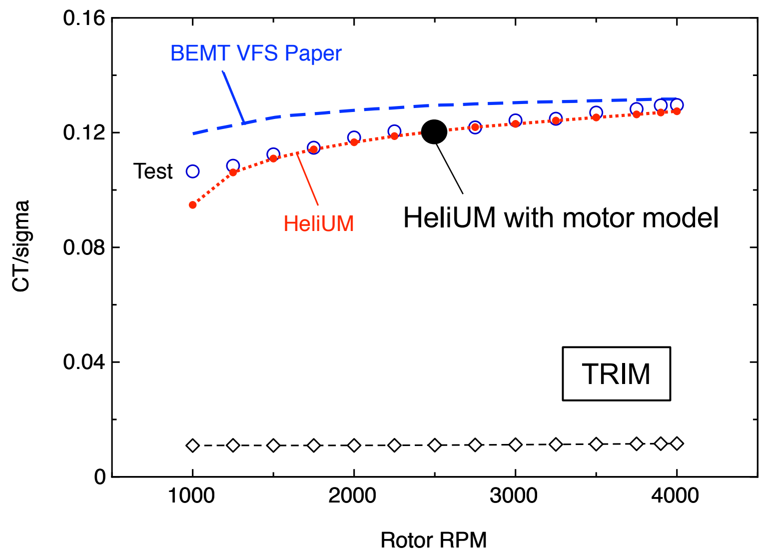

Figure 8: Validation of `HeliUM` trim results with propulsion system model; TRV-80 single rotor on hover test stand.

curve marked "*HeliUM with motor model*" shows the prediction of the improved version of `HeliUM`, developed as part of the present project, with the new propulsion system model. The motor parameters to be used in Eq. (1) were not known. Therefore, they were selected through a small amount of trial and error, to match as closely as possible the experimental results.

The limited validation results of Figs. 8 and 9 indicate that the propulsion system model of Eq. (1) has been correctly implemented in `HeliUM`, and that it can correctly model trim and dynamics of a small rotor such as that of the TRV-80.

5 Remaining Technical Activities

This section briefly lists the activities proposed in the original Statement of Work, including comments on whether or not each activity was completed.

1. *Task 1 — Formulation and Validation of a Multirotor UAS Simulation Model*

   (a) *Subtask 1.1 — Simulation model formulation.* This subtask was composed of two parts: (i) the extension of the simulation with a state-space ODE model of electric motors, and (ii) the additional extension with flexible wing models. The first part was completed, and has been described in the previous sections. The second part was not completed, but work on this extension continues as part of a separate project. The wing model is present in the version `HeliUM-NA` developed at the U.S. Naval Academy, and an effort to merge `HeliUM` and `HeliUM-NA` is currently underway.

   (b) *Subtask 1.2 — Parametric studies of UAS aeromechanics.* This subtask was not completed because the simulation was still being developed when the project

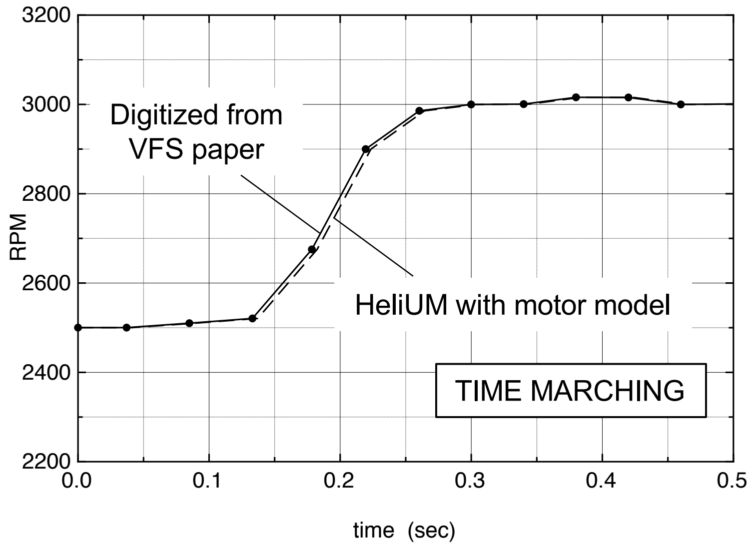

Figure 9: Validation of `HeliUM` time marching simulation results with propulsion system model; TRV-80 single rotor on hover test stand.

was terminated.

(c) *Subtask 1.3 — Simulation model validation.* This subtask was partially completed, as shown in Sec. 4. The results shown in that section are specific to the electric motor modeling, i.e., the main activity of the present project. Many more validation results have been obtained for the general TRV-80 simulation. The validation with wind tunnel and flight test data, including the electric motor model, continues as part of a separate project.

2. *Task 2 — Analysis of the UAS Dynamic Behavior in Simulated Maneuvers and Missions.*

   (a) *Subtask 2.1 — Formulation of the maneuver and mission simulation model.*

   (b) *Subtask 2.2 — Application to specific maneuvers and missions.*

   This task was part of Option Year 2, which was not funded.

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[1] Celi, R., "HeliUM 2 Flight Dynamic Simulation Model: Development, Technical Concepts, and Applications," AHS 71st Annual Forum, Virginia Beach, VA, May 2015.

[2] Ryseck, P., Glover, E. D., Singh, R., Lopez, M. J. S., and Chopra, I., "Steady and Transient Hover Performance Investigation of Electric Medium-sized Variable-RPM Rotor," VFS 78th Annual Forum, Ft. Worth, TX, May 2022.

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[4] Malpica, C., and Withrow-Maser, S., "Handling Qualities Analysis of Blade Pitch and Rotor Speed Controlled eVTOL Quadrotor Concepts for Urban Air Mobility," VFS International Powered Lift Conference 2020, San Jose, CA, Jan. 21-23, 2020.