Preliminary Design Review

In fulfillment of the NASA University Student Launch Initiative requirements

University of Illinois at Urbana-Champaign

Illinois Space Society (ISS)

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ACKNOWLEDGMENT

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Acronyms

CDR Critical Design Review. 6

CFD Computational Fluid Dynamics. 13

CM Center of Mass. 12

CONOPS Concept of Operations. 6

EIA Environmental Impact Assessment. 6

FMEA Failure Modes and Effects Analysis. 6

ISS Illinois Space Society. 6

MoI Moment of Inertia. 12

PDR Preliminary Design Review. 6

PHA Personnel Hazard Analysis. 6

ToI Tensor of Inertia. 12, 13

UAV Unmanned Aerial Vehicle. 11–13

ZOH Zero-order Hold. 17

Contents

Chapter 1

Preface

This document (ISS/USLI-PDR) serves as the Preliminary Design Review (PDR) for the University of Illinois at Urbana-Champaign University Student Launch Initiative team, Illinois Space Society (ISS). The content of this report will chiefly focus on the changes since the original proposal, developments in design and underlying justifications, as well as overall prospects and plans towards the Critical Design Review (CDR). In particular, the launch vehicle design is detailed with reference to the pertinent vehicle requirements, providing an overview of its subsystems, interfaces, and manufacturing methods. Safety considerations are addressed through a multitude of simulations, as well as a qualitative Failure Modes and Effects Analysis (FMEA) and Environmental Impact Assessment (EIA). Following this discussion, the payload requirements and preliminary design of both the airframe and sample retrieval mechanism are presented, culminating in the presentation of a detailed Concept of Operations (CONOPS). The payload–launch vehicle interface as well as the aerial deployment mechanism are discussed, giving rise to a detailed safety analysis. As part of the safety analysis, in addition to a comprehensive FMEA, a Personnel Hazard Analysis (PHA) is presented. Any hazardous activities will be identified as part of this discussion, including any foreseeable contingencies and mitigation procedures. Finally, a project plan is presented, including a project timeline (Gantt chart), bill of materials, list of funding sources and mitigation procedures in case of delays.

This report is composed of six parts, in which each part builds forth upon the previous. These parts are:

I Summary
II Changes
III Launch Vehicle
IV Payload
V Safety
VI Project Plan

Each of these parts describes in due detail the developments and rationale behind the launch vehicle and payload design, as well as the overall implementation.

DISCLAIMER: While the authors have gone through great lengths to ensure the validity of all data presented in this document, all responsibility is assumed for any inconsistencies presented as part of this work.

Part I

Summary

Part II

Changes

Part III

Launch Vehicle

Part IV

Payload

Chapter 2

Quadrotor Dynamic Model

2.1 Coordinate Systems

Let us consider the following four coordinate systems: (i) inertial, (ii) Earth-fixed, (iii) instantaneous topocentric, and (iv) body-fixed [1, pp. 3*f.*]. For these systems, the axes are defined as follows:

Inertial system (O at Earth center)

- **X** On the Earth equatorial plane, pointing to the zero longitude at take-off
- **Y** On the Earth equatorial plane, pointing to the 90° longitude at take-off
- **Z** Perpendicular to the equatorial plane, pointing to the North Pole

Earth-fixed system (O_E at Earth center)

- $\mathbf{X_E}$ On the Earth equatorial plane, always pointing to the Greenwich (0°) longitude
- $\mathbf{Y_E}$ On the Earth equatorial plane, always pointing to the 90° longitude
- $\mathbf{Z_E}$ Perpendicular to the equatorial plane, pointing to the North Pole

Instantaneous topocentric system (O_T at the projection point of the moving Unmanned Aerial Vehicle (UAV) on the Earth surface)

- $\mathbf{x_T}$ On the local horizon plane tangent to the instantaneous projection point of the UAV, directed along the local geocentric North
- $\mathbf{y_T}$ On the local horizon plane tangent to the instantaneous projection point of the UAV, directed along the local geocentric North
- $\mathbf{z_T}$ Perpendicular to the instantaneous tangent plane, directed along the geocentric radius vector and pointing toward the Earth center

Body-fixed system (O_B at the center of gravity of the UAV)

- $\mathbf{x_B}$ Along the UAV principle (longitudinal) axis, positive forward
- $\mathbf{y_B}$ Normal to the x_B–z_B symmetric plane, completing the right-hand system
- $\mathbf{z_B}$ In the principle plane of symmetry of the UAV, perpendicular to the x_B axis and positive downward

We will chiefly confine our discussion to the O_T (instantaneous topocentric system) and O_B (body-fixed) frames, as the distances the vehicle will travel allow for a flat Earth approximation with constant uniform gravity [2]. Let us now consider the coordinate transformation between these two frames:

2.1.1 Coordinate Transformation

Let us define the following Euler angles:

θ Pitch
ψ Yaw
ϕ Roll

We then find the transformation from the instantaneous topocentric frame to the body-centric frame to be [3, Eq. 2-2]:

$$\begin{aligned}[R]_{T\to B}(\theta,\psi,\phi) &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix}\begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix}\begin{bmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \\ &= \begin{bmatrix} \cos\theta\cos\psi & \cos\theta\sin\psi & -\sin\theta \\ \sin\theta\cos\psi\sin\phi - \sin\psi\cos\phi & \sin\theta\sin\psi\sin\phi + \cos\psi\cos\phi & \cos\theta\sin\phi \\ \sin\theta\cos\psi\cos\phi + \sin\psi\sin\phi & \sin\theta\sin\psi\cos\phi - \cos\psi\sin\phi & \cos\theta\cos\phi \end{bmatrix}\end{aligned} \tag{2.1.1}$$

Given the nature of the transformation matrix, it is readily found that:

$$[R]_{B\to T} = [R]^{-1}_{T\to B} = [R]^{\intercal}_{T\to B} \tag{2.1.2}$$

2.2 Dynamic Model

Given the complex nature of the rotor-based UAV, we will make the following a priori assumptions to aid in the derivation of the vehicle model:

1. The UAV is a rigid body.
2. The Tensor of Inertia (ToI) of the UAV is approximated as the Moment of Inertia (MoI) of several objects.
3. The Center of Mass (CM) coincides with the UAV's geometrical centroid.
4. The MoI of the propellers is neglected.
5. Time delay of commands is neglected.
6. Aerodynamic drag force is neglected.

While most of the aforestated simplifications are intuitively sound, neglecting the aerodynamic drag force begs for justification. Castillo et al. [4] provide the following approximation to the UAV drag force:

$$\mathbf{f}_{d_k} = C_{D_k}\rho A_k V_k (V_{w_k} - V_k)\hat{\mathbf{k}}, \quad k : x_b, y_b, z_b \tag{2.2.1}$$

Where $\hat{\mathbf{k}}$ is the unit vector in $\mathbf{k}$ direction, A_k is the reference area by which the drag coefficient C_{D_k} is determined in the $\mathbf{k}$-direction. V_k and V_{w_k} are the vehicle velocity and wind velocity in O_B, respectively, and ρ is the air density, which is assumed to be constant. In this formulation, C_{D_k} is to be determined through simulation (Computational Fluid Dynamics (CFD)) or experiment. However, this poses a significant difficulty: the UAV consists of many distinct components with orientation and speed dependent drag characteristics, making the definition of a constant C_{D_k} inadvisable. As a matter of fact, Castillo et al. [4] treat the drag force as an unknown disturbance that is to be counteracted by the control system, thus warranting the term to be dropped.

Let us define $\mathbf{T}$ and $\mathbf{H}$, the thrust force and hub torque for every motor–propeller system, respectively. Research shows that these forces scale with the square of the angular rate of the propellor [3–7], i.e.:

$$T_i = k_T \omega_i^2 \tag{2.2.2}$$

$$H_i = k_H \omega_i^2 \tag{2.2.3}$$

where i denotes the i'th propeller, and we assume the propellers to be identical, yielding constant k_T, k_H. These coefficients can be found experimentally. Following the Newton–Euler approach presented by Kurak and Hodzic [3], we find for a symmetric four-propeller UAV layout:

$$\ddot{\phi} = \frac{\ell(T_2 - T_4) - (I_z - I_y)\dot{\theta}\dot{\psi}}{I_x} \tag{2.2.4}$$

$$\ddot{\theta} = \frac{\ell(T_3 - T_1) - (I_x - I_z)\dot{\phi}\dot{\psi}}{I_y} \tag{2.2.5}$$

$$\ddot{\psi} = \frac{(H_1 + H_3) - (H_2 + H_4) - (I_y - I_x)\dot{\phi}\dot{\theta}}{I_z} \tag{2.2.6}$$

$$\ddot{x} = \frac{(\cos\phi \sin\theta \cos\psi + \sin\phi \sin\psi) \sum_{i=1}^{4} T_i}{m} \tag{2.2.7}$$

$$\ddot{y} = \frac{(\cos\phi \sin\theta \sin\psi - \sin\phi \cos\psi) \sum_{i=1}^{4} T_i}{m} \tag{2.2.8}$$

$$\ddot{z} = \frac{(\cos\phi \cos\theta) \sum_{i=1}^{4} T_i - mg}{m} \tag{2.2.9}$$

where $I_k = I_{kk}, k : x, y, z$ are the diagonal elements of the ToI $\mathbf{I}$, ℓ is the L_2-distance between the propeller and the origin of the O_B-frame (ℓ is constant to satisfy symmetry).

2.2.1 Nonlinear state space model

Let us define the following state variable:

$$\mathbf{x} = \begin{bmatrix} \phi \\ \dot{\phi} \\ \theta \\ \dot{\theta} \\ \psi \\ \dot{\psi} \\ z \\ \dot{z} \\ x \\ \dot{x} \\ y \\ \dot{y} \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 = \dot{x}_1 \\ x_3 \\ x_4 = \dot{x}_3 \\ x_5 \\ x_6 = \dot{x}_5 \\ x_7 \\ x_8 = \dot{x}_7 \\ x_9 \\ x_{10} = \dot{x}_9 \\ x_{11} \\ x_{12} = \dot{x}_{11} \end{bmatrix} \tag{2.2.10}$$

The force control input is then defined as:

$$\mathbf{u}^* = \begin{bmatrix} \sum_{i=1}^4 T_i \\ T_2 - T_4 \\ T_3 - T_1 \\ (H_1 + H_3) - (H_2 + H_4) \end{bmatrix} \tag{2.2.11}$$

Defining the angular rate control input as:

$$\mathbf{u} = \begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{bmatrix} \tag{2.2.12}$$

Using this definition, we find the force control input $\mathbf{u}^*$ to be related to the angular rate control input $\mathbf{u}$ as follows:

$$\mathbf{u}^* = \begin{bmatrix} k_T & k_T & k_T & k_T \\ 0 & k_T & 0 & -k_T \\ -k_T & 0 & k_T & 0 \\ k_H & -k_H & k_H & -k_H \end{bmatrix} \mathbf{u} \tag{2.2.13}$$

Let us now define the following constants:

$$a_1 = \frac{I_y - I_z}{I_x} \qquad a_2 = \frac{I_z - I_x}{I_y} \qquad a_3 = \frac{I_x - I_y}{I_z} \tag{2.2.14}$$

$$b_1 = \frac{\ell}{I_x} \qquad b_2 = \frac{\ell}{I_y} \qquad b_3 = \frac{\ell}{I_3} \tag{2.2.15}$$

and the following rotations:

$$\begin{aligned}
r_t &= \cos\phi\cos\theta \\
r_x &= \cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi \\
r_y &= \cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi
\end{aligned} \tag{2.2.16}$$

The nonlinear state space formulation is then found to be:

$$\dot{\mathbf{x}} = \begin{bmatrix} x_2 \\ x_4 x_6 a_1 + b_1 u_2^* \\ x_4 \\ x_2 x_6 a_2 + b_2 u_3^* \\ x_6 \\ x_2 x_4 a_3 + b_3 u_4^* \\ x_8 \\ -g + r_t(x_1, x_3) u_1^*/m \\ x_{10} \\ r_x(x_1, x_3, x_5) u_1^*/m \\ x_{12} \\ r_y(x_1, x_3, x_5) u_1^*/m \end{bmatrix} \tag{2.2.17}$$

2.2.2 Linearized state space model

Let us apply a small angle approximation on Eq. 2.2.16, giving:

$$\begin{aligned}
r_t &\approx 1 \\
r_x &\approx \theta \\
r_y &\approx \theta\psi - \phi \approx -\phi
\end{aligned} \tag{2.2.18}$$

To linearize Eq. 2.2.17, we must find a suitable equilibrium point, where $\dot{\mathbf{x}} = \mathbf{0}$. This holds for:

$$\begin{aligned}
\bar{\mathbf{x}} &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & \bar{x}_7 & 0 & \bar{x}_9 & 0 & \bar{x}_{11} \end{bmatrix}^\intercal \\
\bar{\mathbf{u}}^* &= \begin{bmatrix} mg & 0 & 0 & 0 \end{bmatrix}^\intercal
\end{aligned} \tag{2.2.19}$$

Linearizing Eq. 2.2.17 about $(\bar{\mathbf{x}}, \bar{\mathbf{u}}^*)$, we obtain:

$$\begin{aligned}
\mathbf{A} &= \left.\frac{\partial \dot{\mathbf{x}}(\mathbf{x},\mathbf{u}^*)}{\partial \mathbf{x}}\right|_{(\bar{\mathbf{x}},\bar{\mathbf{u}}^*)} \\
\mathbf{B} &= \left.\frac{\partial \dot{\mathbf{x}}(\mathbf{x},\mathbf{u}^*)}{\partial \mathbf{u}^*}\right|_{(\bar{\mathbf{x}},\bar{\mathbf{u}}^*)}
\end{aligned} \tag{2.2.20}$$

which yields the following state space formulation:

$$
\begin{aligned}
\dot{\mathbf{x}} &= \underbrace{\begin{bmatrix}
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0\\
0 & g & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1\\
-g & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}}_{\mathbf{A}} \mathbf{x} + \underbrace{\begin{bmatrix}
0 & 0 & 0 & 0\\
0 & b_1 & 0 & 0\\
0 & 0 & 0 & 0\\
0 & 0 & b_2 & 0\\
0 & 0 & 0 & 0\\
0 & 0 & 0 & b_3\\
0 & 0 & 0 & 0\\
1/m & 0 & 0 & 0\\
0 & 0 & 0 & 0\\
0 & 0 & 0 & 0\\
0 & 0 & 0 & 0\\
0 & 0 & 0 & 0
\end{bmatrix}}_{\mathbf{B}^*} \mathbf{u}^* \\
&= \mathbf{A}\mathbf{x} + \underbrace{\begin{bmatrix}
0 & 0 & 0 & 0\\
0 & b_1 k_T & 0 & -b_1 k_T\\
0 & 0 & 0 & 0\\
-b_2 k_T & 0 & b_2 k_T & 0\\
0 & 0 & 0 & 0\\
b_3 k_H & -b_3 k_H & b_3 k_H & -b_3 k_H\\
0 & 0 & 0 & 0\\
\frac{k_T}{m} & \frac{k_T}{m} & \frac{k_T}{m} & \frac{k_T}{m}\\
0 & 0 & 0 & 0\\
0 & 0 & 0 & 0\\
0 & 0 & 0 & 0\\
0 & 0 & 0 & 0
\end{bmatrix}}_{\mathbf{B}} \mathbf{u}
\end{aligned}
\tag{2.2.21}
$$

2.2.3 Discretization

Zero-order Hold (ZOH) discretization of Eq. 2.2.21, gives for constant sampling time h:

$$\mathbf{\Phi} = e^{\mathbf{A}h} = \begin{bmatrix} 1 & h & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & h & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & h & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & h & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & \frac{gh^2}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 1 & h & 0 & 0 \\ 0 & gh & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ -\frac{gh^2}{2} & -\frac{gh^3}{6} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & h \\ -gh & -\frac{gh^2}{2} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\mathbf{\Gamma} = \int_0^h e^{\mathbf{A}s}\,\mathrm{d}s \cdot \mathbf{B} = \begin{bmatrix} 0 & \frac{1}{2}b_1h^2k_T & 0 & -\frac{1}{2}b_1h^2k_T \\ 0 & b_1hk_T & 0 & b_1(-h)k_T \\ -\frac{1}{2}b_2h^2k_T & 0 & \frac{1}{2}b_2h^2k_T & 0 \\ b_2(-h)k_T & 0 & b_2hk_T & 0 \\ \frac{1}{2}b_3h^2k_H & -\frac{1}{2}b_3h^2k_H & \frac{1}{2}b_3h^2k_H & -\frac{1}{2}b_3h^2k_H \\ b_3hk_H & b_3(-h)k_H & b_3hk_H & b_3(-h)k_H \\ \frac{h^2k_T}{2m} & \frac{h^2k_T}{2m} & \frac{h^2k_T}{2m} & \frac{h^2k_T}{2m} \\ \frac{hk_T}{m} & \frac{hk_T}{m} & \frac{hk_T}{m} & \frac{hk_T}{m} \\ 0 & \frac{1}{6}b_1gh^3k_T & 0 & -\frac{1}{6}b_1gh^3k_T \\ 0 & \frac{1}{2}b_1gh^2k_T & 0 & -\frac{1}{2}b_1gh^2k_T \\ 0 & -\frac{1}{24}b_1gh^4k_T & 0 & \frac{1}{24}b_1gh^4k_T \\ 0 & -\frac{1}{6}b_1gh^3k_T & 0 & \frac{1}{6}b_1gh^3k_T \end{bmatrix} \tag{2.2.22}$$

with the following state space system:

$$\mathbf{x}(k+1) = \mathbf{\Phi}\mathbf{x}(k) + \mathbf{\Gamma}\mathbf{u}(k) \tag{2.2.23}$$

2.3 Simulation

From Tayebi and McGilvray [8], we adopt the following values for our simulation:

Table 2.1: Simulation parameters [8]

Parameter	Value
g	$9.81\,\mathrm{m\,s^{-2}}$
m	$0.468\,\mathrm{kg}$
ℓ	$0.225\,\mathrm{m}$
k_T	$2.980\times10^{-6}\,(\mathrm{rad}^2/\mathrm{s}^2)/\mathrm{N}$
k_H	$1.140\times10^{-7}\,(\mathrm{rad}^2/\mathrm{s}^2)/\mathrm{Nm}$
I_x	$4.856\times10^{-3}\,\mathrm{kg\,m^{-2}}$
I_y	$4.856\times10^{-3}\,\mathrm{kg\,m^{-2}}$
I_z	$8.801\times10^{-3}\,\mathrm{kg\,m^{-2}}$

Letting $h = 1\times10^{-3}$ s, we obtain:

$$
\begin{aligned}
\mathbf{\Phi} &= \begin{bmatrix}
1 & 0.001 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0.001 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0.001 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0.001 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 4.905\times10^{-6} & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0.001 & 0 & 0 \\
0 & 0.00981 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
-4.905\times10^{-6} & -1.635\times10^{-9} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0.001 \\
-0.00981 & -4.905\times10^{-6} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix} \\
\mathbf{\Gamma} &= \begin{bmatrix}
1 & 0.001 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0.001 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0.001 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0.001 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 4.905\times10^{-6} & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0.001 & 0 & 0 \\
0 & 0.00981 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
-4.905\times10^{-6} & -1.635\times10^{-9} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0.001 \\
-0.00981 & -4.905\times10^{-6} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\end{aligned}
\tag{2.3.1}
$$

Part V

Safety

Part VI

Project Plan

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