Sliding Mode Control Approaches for an Autonomous Unmanned Airship

Fábio Pereira Benjovengo†, Ely Carneiro de Paiva*, Samuel Siqueira Bueno‡
Centro de Tecnologia da Informação Renato Archer - CTI
Rod. D. Pedro I, km 143,6 – 13082-120 – Campinas - Brazil
fabio991737@gmail.com, ely.paiva@cti.gov.br

Paulo Augusto Valente FerreiraΘ
Faculdade de Engenharia Elétrica - UNICAMP
Av. Albert Einstein 400, Campinas – Brazil
valente@dt.fee.unicamp.br

[Abstract] This paper presents the research developments for the global nonlinear control of an autonomous airship, covering the full flight envelope from hovering to aerodynamic flight. It focuses on the longitudinal control of the airship using two different Sliding Mode control techniques that are the classical sliding mode and the unit vector approach. The design methodologies for both techniques are presented along with some representative simulation results.

I. Introduction

A great interest in the utilization of unmanned aerial vehicles appeared in the last fifteen years, due to their potential application in varied tasks such as surveillance, advertising, monitoring, inspection, exploration, and research roles. A new and special attention has been given to the use of unmanned aerial vehicles in environmental applications, such as bio-diversity, ecological, climatic, and agricultural research and monitoring, among others. The data gathered by UAVs can also be used in a complementary way concerning information obtained by satellites, balloons, manned aircraft or on ground.

Most of these applications for environmental purposes have profiles that require maneuverable low altitude, low speed airborne data gathering platforms. The vehicle should ideally be able to hover above an area, present extended airborne capabilities for long duration studies, take-off and land vertically without the need of runway infrastructures, have a large payload to weight ratio, among other requisites. For this scenario, lighter-than-air (LTA) vehicles are better suited than airplanes and helicopters mainly because: they derive the largest part of their lift from aerostatic, rather than aerodynamic forces; they are safer and, in case of failure, present a graceful degradation; they are intrinsically of higher stability than other platforms. In this context, Project AURORA - Autonomous Unmanned Remote mQnitoring Robotic Airship – was proposed. AURORA focuses on the establishment of the technologies required to substantiate autonomous operation of unmanned robotic airships for environmental monitoring and aerial inspection missions. This includes sensing and processing infrastructures, control and guidance capabilities, and the ability to perform mission, navigation, and sensor deployment planning and execution.

Aiming the autonomous airship goal, aerial platform positioning and path tracking should be assured by a control and navigation system. Such a system needs to cope with the highly nonlinear, flight-dependent and underactuated airship dynamics, ranging from the hovering flight (HF) to the aerodynamic flight (AF) or cruise flight. Hovering flight is defined here as a flight at low airspeed condition.

Basically, two main approaches can be considered for the automatic control and navigation system of an airship. The first one relies on the linear control theory to design individual compensators to satisfy closed-loop

† Graduate Student, DRVC/CTI, Rod. D. Pedro I, km 143,6 – 13082-120 – Campinas – Brazil.
* Research Engineer, DRVC/CTI, Rod. D. Pedro I, km 143,6 – 13082-120 – Campinas – Brazil.
‡ Research Engineer, DRVC/CTI, Rod. D. Pedro I, km 143,6 – 13082-120 – Campinas – Brazil.
Θ Professor FEEC/Unicamp Av. Albert Einstein 400 – Campinas – Brazil.
specifications, based on linearized models of the airship dynamics. The linear based controllers may be a sufficient solution for some kind of specific applications, especially in the aerodynamic flight\textsuperscript{1,3}. We can cite the experimental results obtained for the AURORA airship for path following in AF (and with constant airspeed) through a set of pre-defined points in latitude/longitude, along with an automatic altitude control reported in Ramos et al.\textsuperscript{4} and de Paiva et al.\textsuperscript{5} However, for applications where the airspeed (and thus the dynamics) has a large range of variation, the linearized controllers may not yield a good performance.

In this case, the search for a global nonlinear control scheme covering the full flight envelope from HF to AF is strongly recommended. The main challenges for the control system are the nonlinear and abrupt behavior change of the dynamics between the HF and AF zones, the very different dynamics in low and high airspeeds, and the modeling uncertainties. Two nonlinear control solutions are under investigation for the AURORA airship at present, namely Backstepping\textsuperscript{6,19,25}, and the Sliding Mode Control\textsuperscript{7,12}. The preliminary reports for the Backstepping approaches were presented in the previous AIAA-LTA conference\textsuperscript{6,19,12}. In the present work, the last results on the Sliding Mode technique for the longitudinal control of the airship are shown. The Sliding Mode Control (SMC) is a class of nonlinear, variable structure method, presenting one or more discontinuities in the space of states of a system\textsuperscript{12}. Therefore, the structure of the system is changed or switched each time the state crosses this discontinuous surface, called sliding surface. It is a powerful control technique yielding high robustness to model uncertainty and external disturbances. SMC is commonly used in the control of ROVs\textsuperscript{13} and also in the aeronautics field\textsuperscript{14}.

We present here the design and simulation results for two different approaches of Sliding Mode Control: i) Classical Multivariable Sliding Mode\textsuperscript{10,11}, ii) Unit Vector approach\textsuperscript{14,15}. By now, the control law was designed and implemented using force inputs only. Both SM approaches differ basically in the design of the sliding surface and also in the fact that the second one (Unit Vector) includes a feedforward input coming from an ideal model reference. The two techniques were compared regarding robustness, accuracy (offset errors) and complexity in the design and in the control law. The comparative simulation was done using the AURORA Simulation environment\textsuperscript{11}. In this simulated test the airship was submitted to large variations in the airspeed (0-15 m/s), while receiving commands to follow given altitude and velocity profiles.

In the sequel, we present the design of the two sliding mode approaches along with the comparative results. The nonlinear control design is the main subject of the ongoing research of Project AURORA, and the better approach among Backstepping and Sliding Mode Control will be selected for future application in the airship onboard control and navigation system.

II. Nonlinear Airship Dynamics

For the current phase of the Project AURORA, the LTA robotic prototype has been built as an evolution of the Airspeed Airships’ AS800. It is a non-rigid airship with 10.5 m long, 3.0 m diameter, and 34 m$^3$ of volume, whose payload capacity is approximately 10 kg and maximum speed is around 50 km/h (Fig. 1).

In order to develop an accurate mathematical model of the airship flight dynamics, the following aspects were taken into account\textsuperscript{13}: (i) the model considers the airship virtual masses and inertias due to the large volume of air displaced by the airship; (ii) the airship motion is referenced to a system of orthogonal axes fixed to the vehicle, whose origin is the Center of Volume (CV), assumed to coincide with the gross Center of Buoyancy (CB) (see Figure 2); (iii) the airship is assumed to be a rigid body, so that aero elastic effects are ignored.

Figure 1. AURORA I LTA robotic prototype.
The dynamic model is defined in the airship frame. The orientation of this body-fixed frame (X, Y, Z) with respect to an Earth-fixed frame (XE, YE, ZE) is obtained through the Euler angles (φ, θ, ψ), corresponding to the roll, pitch and yaw angles, respectively. The airship linear and angular velocities are given by (u, v, w) and (p, q, r), respectively. Taking into account the above assumptions, the airship dynamics may be expressed as:

\[
M\ddot{V} = F_d(V) + F_a(V) + F_p + F_g
\]  

where \( M \) is the 6x6 mass matrix that includes both the actual inertia of the airship and the virtual inertia elements associated with the dynamics of buoyant vehicles; \( V = [u, v, w, p, q, r]^T \) is the 6x1 vector of airship velocities; \( F_d \) is the 6x1 dynamics vector containing the Coriolis and centrifugal force terms, and also the wind-induced forces; \( F_a \) is the 6x1 vector of aerodynamic forces and moments; \( F_p \) is the 6x1 vector of propulsion forces and moments, and \( F_g \) is the 6x1 gravity forces and moments, which are function of the difference between the weight and buoyancy forces.

As main control actuators (Figure 2), the AS800 airship has four deflection surfaces, and a pair of propellers driven by two engines. The four deflection surfaces at the tail are arranged in a ‘×’ shape, but they generate the equivalent rudder and elevator commands of the classical ‘+’ tail, with allowable deflections situated in the range -25 to +25 degrees. The main propellers generate the necessary forces to control the airship motion. Their vectoring (ranging from -30 to +120 degrees up) is used for vertical load compensation and to control the longitudinal motion at low airspeed. Additionally, a stern horizontal electric thruster is used in the low speed operation.

![Figure 2. Airship local reference frame (left) and airship main actuators (right).](image)

### III. Sliding Modes: the Classical Approach

The Sliding Mode Control (SMC) is a class of nonlinear, variable structure method, presenting one or more discontinuities in the space of states of a system. Therefore, the structure of the system is changed or switched each time the state crosses this discontinuous surface, called sliding surface. A possible drawback is that the control signal tends to switch around the zero error region giving a high frequency input to the control actuator, called chattering. However this can be avoided by the use of a soft (or pseudo) switching structure. It is a powerful control technique yielding high robustness to model uncertainty and external disturbances. SMC is commonly used in the control of ROVs, and also in the aeronautics field.

The MIMO SMC developed in this first phase is adapted from the approach presented in Healey and Lienard. A longitudinal controller to follow a given altitude and velocity profile is derived based on linearized models of the airship. Although the design of the SMC controllers relies in the model linearization for a given airspeed, the results are however applied to a wide range of airspeeds due to the high robustness of the nonlinear switching control. A methodology is presented for the derivation of the sliding surface, and the bounded stability is proved. In order to evaluate the approach, a representative simulation test was performed, using the 6 DOF airship simulation environment, where the airship is submitted to a large variation in airspeed.

In the sequel, the derivation of the classical sliding mode control law for the longitudinal mode of the AURORA airship is presented. Firstly, let us adapt the airship dynamics and kinematics from (1), to the following equations:
where \( \mathbf{v} \) and \( \mathbf{p} \) are the velocity and position state vectors, with \( f, g, h \) as nonlinear functions, and \( \mathbf{u} \) is the control input vector. Or in other words \( \mathbf{v} = [u \ w \ q]^T \) corresponding to the forward velocity, vertical velocity and pitch rate, and \( \mathbf{p} = [\theta \ h]^T \) corresponding to pitch angle and altitude. The control input is given by \( \mathbf{u} = [F_u \ F_w \ F_q]^T \) corresponding to the forward and vertical forces and the pitching moment, respectively.

The output \( \mathbf{y} \) is required to follow a given reference \( \mathbf{y}_{com} \), such that the error \( \mathbf{e} = \mathbf{y} - \mathbf{y}_{com} = [\mathbf{v}^T \ \mathbf{p}^T]^T \) tends to zero with global stability. The objective of the design of the SMC is to define the sliding hyperplane \( \mathbf{S} \), and a discontinuous control law ensuring that the error state attains a sliding mode. The hyperplane in the error space is given by:

\[
\mathbf{S} = \mathbf{S}_1 \begin{bmatrix} \mathbf{v} \\ \mathbf{p} \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} \mathbf{v} \\ \mathbf{p} \end{bmatrix}
\]

Let us assume the linearized error dynamics/kinematics for a given trimmed condition as

\[
\begin{bmatrix} \dot{\mathbf{v}} \\ \dot{\mathbf{p}} \end{bmatrix} = \begin{bmatrix} A_1 & A_2 \\ A_3 & A_4 \end{bmatrix} \begin{bmatrix} \mathbf{v} \\ \mathbf{p} \end{bmatrix} + \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} \mathbf{u} + \mathbf{f}
\]

where \( \mathbf{f} \) denotes the differences between the linear and nonlinear models. And let us propose the following control law for the system as

\[
\mathbf{u}(t) = \mathbf{F}(\sigma) + \mathbf{u}_{switching}
\]

where the superscript “\(^+\)” denotes the pseudoinverse, and \( \mathbf{F}(\sigma) = \mathbf{F}_{equivalent} + \mathbf{F}_{switching} \) in \( \mathbf{F}(\sigma) \), whose components are defined as

\[
\mathbf{F}_{\sigma}(\sigma) = \eta \ \text{sgn}(\sigma(\mathbf{v}, \mathbf{p}))
\]

where \( \eta \) are positive constant parameters. Supposing that matrix \( \mathbf{B} \) is full rank, we can select matrix \( \mathbf{S}_1 \) as identity, and the substitution of the control law (4) in (3) leads to

\[
\begin{bmatrix} \dot{\mathbf{v}} \\ \dot{\mathbf{p}} \end{bmatrix} = \begin{bmatrix} A_3 & A_4 \\ -S_2 A_3 & -S_2 A_4 \end{bmatrix} \begin{bmatrix} \mathbf{v} \\ \mathbf{p} \end{bmatrix} + \begin{bmatrix} \mathbf{F}(\sigma) \\ 0 \end{bmatrix} + \mathbf{f}
\]

such that

\[
\dot{\sigma}(\mathbf{v}, \mathbf{p}) = \mathbf{S}_1 \begin{bmatrix} \mathbf{v} \\ \mathbf{p} \end{bmatrix} = -\mathbf{F}(\sigma) + \mathbf{f}
\]

The global stability of \( \sigma \) will now be proved. Let us consider the Lyapunov function

\[
V(\sigma) = \frac{1}{2} \sigma^T(\mathbf{v}, \mathbf{p}) \sigma(\mathbf{v}, \mathbf{p})
\]

where \( V \) is positive definite. Then, from (5) and (7), and considering sufficiently high gains \( \eta \), the global asymptotic stability of the system is assured as
\[
\frac{d V(\sigma)}{dt} = \dot{\sigma}^T \sigma < 0
\]

However, to avoid the usual chattering problems, associated to the switching control, it is necessary to redefine \( F(\sigma) \) in (5) as

\[
F_i(\sigma) = \eta_i \tanh(\sigma_i(\tilde{v}, \tilde{p}) / \phi_i)
\]  

(8)

where the parameters \( \phi_i \) are used to adjust the chattering smoothing. And in this case, the asymptotic stability turns into a bounded stability.

Now, let us derive the system dynamics in the sliding surface, when we have \( \sigma = 0 \). In this case, the substitution of \( F(\sigma) = 0 \) in (6), and supposing matched dynamics (\( \delta f = 0 \)) leads to

\[
\begin{bmatrix}
\dot{\tilde{v}} \\
\dot{\tilde{p}}
\end{bmatrix} =
\begin{bmatrix}
-S_2A_3 & -S_2A_4 \\
A_3 & A_4
\end{bmatrix}
\begin{bmatrix}
\tilde{v} \\
\tilde{p}
\end{bmatrix}
\]

Such that in the sliding condition, not only \( \sigma \), but also \( \dot{\sigma} \) will vanish, as \( \dot{\sigma} = [S_1 \quad S_2] \).

Therefore, the dynamics of the system in the sliding surface is given by the choice of matrix \( S_2 \). As we have \( \sigma = 0 \), as well \( \dot{\sigma} = 0 \) and \( S_1 = I \), we can consider \( \tilde{v} = -S_2 \tilde{p} \), such that the dynamics of \( \tilde{p} \) can be specified by the closed loop matrix \( A_c \) or

\[
\dot{\tilde{p}} = A_c \tilde{p} \quad \text{where} \quad A_c = (A_4 - A_3S_2)
\]

Assuming that the pair \((A_4, A_3)\) is controllable, then \( S_2 \) can be determined through pole placement or LQR solution. Therefore, the dynamics of the vehicle in the sliding condition has the same number of integrators as the number of control actuators.

Thus, with \( S_1 \) and \( S_2 \) determined, the control law in (4) is defined. The choice of parameters \( \eta \) and \( \phi \) depends on the level of activity desired for the respective actuators input, and the level of the reducing (smoothing) in chattering. Therefore, the closed loop system dynamics is represented by a \textit{sliding manifold}, that is a hyperplane in the error space, which the controller strives to converge the system toward. The switching term is effective when the system diverges from this zero sliding surface, forcing it to come back (despite the unmodeled dynamics and nonlinearities), and the equivalent controller is effective when upon the sliding manifold.

### IV. Sliding Modes: the Unit Vector Approach

This section presents a slightly different approach of the sliding mode control technique. Although the control law continues to be switched according to a switching surface, the design of the non-linear control law is different. Due to the switching property of the controller, chattering is a concern and must be avoided. The advantage of this control technique is high robustness to model uncertainties and external disturbances.

The MIMO SMC developed in this section is adapted from the approach presented in Edwards and Spurgeon\(^{24}\). The controller derived is based on linearized models of the airship. Although the design of the SMC controllers relies in the model linearization for a given airspeed, the results are however applied to a wide range of airspeeds due to the high robustness of the nonlinear switching control. A methodology is presented for the derivation of the sliding surface, and the bounded stability is proved. In order to evaluate the approach, a representative simulation test was performed, where the airship is submitted to a large variation in airspeed.

Along with this new approach to the sliding mode control design, this section carries out the design of a model reference to the system. As shown in Edwards and Spurgeon\(^{24}\), it is not possible for any system to follow an arbitrary model reference without asymptotical tracking errors and some conditions should be matched in this case.

Consider the longitudinal dynamics of a blimp described in (2) and its linearization for a given trimmed condition.
\[
\begin{align*}
\dot{\mathbf{x}}(t) &= \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) \\
\mathbf{y}(t) &= \mathbf{C}\mathbf{x}(t)
\end{align*}
\]

(9)

where \(\mathbf{x}(t)\) comprises the information about \(\mathbf{v}\) and \(\mathbf{p}\) of equation (2).

A model reference for this linearized system must contain the desired specification of each state of the system. As described in Edwards and Spurgeon \(^{24}\), the system will be able to follow the model reference if its dynamics can be described as

\[
\begin{align*}
\dot{\mathbf{x}}_m(t) &= \mathbf{A}_m\mathbf{x}_m(t) + \mathbf{B}_m\mathbf{r}(t) \\
\mathbf{y}_m(t) &= \mathbf{C}\mathbf{x}_m(t)
\end{align*}
\]

(10)

for \(\mathbf{A}_m = \mathbf{A} + \mathbf{BF}\) and \(\mathbf{B}_m = -\mathbf{B}\left(\mathbf{CA}_m^{-1}\mathbf{B}\right)^{-1}\), where \(\mathbf{F}\) is an appropriate sized matrix and \(\mathbf{r}(t)\) is the reference to be followed. Important features of this method are the possibility of decoupling oscillatory modes, or, in the case of controlling a blimp, minimize the influence of the speed in altitude. If the model reference matrices satisfy the requirements for tracking, then it is possible for the system to track the states \(\mathbf{x}_m(t)\).

Define the error state as the difference between the model reference states and the blimp states

\[
\mathbf{e}(t) = \mathbf{x}(t) - \mathbf{x}_m(t) \quad \text{and} \quad \dot{\mathbf{e}}(t) = \dot{\mathbf{x}}(t) - \dot{\mathbf{x}}_m(t).
\]

(11)

Replacing equations (9) and (10) into equation (11), the error dynamics can be written as

\[
\dot{\mathbf{e}}(t) = \mathbf{A}_m\mathbf{e}(t) + (\mathbf{A} - \mathbf{A}_m)\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) - \mathbf{B}_m\mathbf{r}(t).
\]

(12)

The aim of the design of the SMC is to define the sliding hyperplane \(\sigma(t)\) and the discontinuous control law ensuring that the error state between the model reference and the states of the blimp attains a sliding mode. The hyperplane in the error space is defined to be

\[
\sigma(e) = \mathbf{Se}(t).
\]

(13)

During the sliding modes, \(\sigma(e) = 0\) and \(\dot{\sigma}(e) = 0\). In this case, from equation (12) it is possible to write the error dynamics in the sliding mode as

\[
\dot{\mathbf{e}}(t) = (\mathbf{I} - \mathbf{B}(\mathbf{SB})^{-1}\mathbf{S})\mathbf{A}_m\mathbf{e}(t),
\]

where \(\mathbf{I}\) is an identity matrix of appropriate size. So the error state \(\mathbf{e}(t)\) should be in the null space of the matrix \(\mathbf{S}\). Transforming the linearized system dynamics into its regular form \(^{24}\) and using the performance index \(\mathbf{Q}\), the switching matrix \(\mathbf{S}\) is defined to be

\[
\mathbf{S} = [\mathbf{Q}_{22}^{-1}\left(\mathbf{A}_{12}\mathbf{P}_1 + \mathbf{Q}_{21}\right) - \mathbf{I}]\mathbf{Tr} ,
\]

(14)

where \(\mathbf{A}_{ij}\) and \(\mathbf{Q}_{ij}\) are partitions of \(\mathbf{A}\) and \(\mathbf{Q}\) in the regular form, \(\mathbf{Tr}\) is the transform matrix for the regular form, \(\mathbf{I}\) is an appropriate sized identity matrix and \(\mathbf{P}_1\) is a positive definite solution to the algebraic matrix Riccati equation

\[
\mathbf{P}_1\dot{\mathbf{A}} + \dot{\mathbf{A}}^\top\mathbf{P}_1 - \mathbf{P}_1\mathbf{A}_2\mathbf{Q}_{22}^{-1}\mathbf{A}_2^\top\mathbf{P}_1 + \dot{\mathbf{Q}} = 0 ,
\]
for $\hat{A} = A_{11} - A_{12}Q_{22}^{-1}Q_{21}$ and $\hat{Q} = Q_{11} - Q_{12}Q_{22}^{-1}Q_{21}$.

The control law must now be designed to ensure that the error state $\mathbf{e}(t)$ tends to zero. So the error state and its derivatives must equal zero as $t \to \infty$. From equations (9), (10) and (12), the error dynamics for the nonlinear system can be written as

$$\dot{\mathbf{e}}(t) = A_m\mathbf{e}(t) + (A - A_m)\mathbf{x}(t) + B(u(t) + f(t, x, u)) - B_m\mathbf{r}(t),$$

where $f(t, x, u)$ is a non-linear function that represents the system's uncertainties.

To derive the control law so that the error states attain a sliding mode, consider the Lyapunov function

$$V(\sigma) = \frac{1}{2}\sigma^T(\sigma) \text{ and } \dot{V}(\sigma) = \dot{\sigma}^T(\sigma).$$

For $V(\sigma) > 0$ and $\dot{V}(\sigma) < 0$ for all $t > 0$, considering equations (12), (13) and the switching matrix $S$ defined by (14), a possible choice of the control law is

$$u(t) = u_1(t) + u_n(t) + u_2(t),$$

where

$$u_1(t) = -(SB)^{-1}(SA_m - \Phi S)e(t),$$

$$u_n(t) = -p(t, e)(SB)^{-1}\frac{P_2\sigma(e)}{\|P_2\sigma(e)\| + \delta},$$

$$u_2(t) = Fx(t) + Gr(t),$$

where $p(t, e)$ is the nonlinear control gain considered here as constant, $\Phi$ and $P_2$ are design matrices, $F$ and $G$ are defined by the model reference and $\delta$ is used to avoid the chattering phenomenon.

### V. Simulation Results

In order to validate both approaches for the Sliding Mode Control methodology, a simulation test was performed, using a 6 DOF nonlinear model based simulation environment. The trimmed condition used to derive the linearized dynamics of the airship is

$$u_i = 7m/s, \quad \theta_i = 3.11^\circ, \quad D_i = -50m.$$  

The groundspeed reference varies from 3 m/s to 12 m/s (from HF to AF) and the height varies from 50 m to 70 m. This airspeed variation implies an aggressive variation for the control system, since it ranges from hovering to aerodynamic flight.

The parameters and matrices (linearized for an airspeed of 7 m/s) of the longitudinal control law according to (4) are:

$$v=[u w q]^T \quad p=[\theta h]^T \quad u=[F_u F_w F_q]^T \quad \eta=[2 2 20]^T \quad \phi=[0.25 0.25 0.25]^T$$
A model reference that comprises the information about the desired dynamics of the airship is used along with the Unit Vector approach and is given by

\[
\begin{bmatrix}
-0.1182 & 0.2364 & 2.0523 & -0.3770 & 0.0000 \\
-0.0132 & -0.6116 & 7.9733 & -0.0630 & 0.0000 \\
0.0377 & -0.3528 & -4.6869 & -1.1354 & 0.0000 \\
0.0000 & 0.0000 & 1.0000 & 0.0000 & 0.0000 \\
0.0000 & -1.0000 & 0.0000 & 8.0000 & 0.0000
\end{bmatrix}
\]

\[
A = \begin{bmatrix}
0.0223 & 0.0000 & -0.0023 \\
0.0000 & 0.0123 & 0.0000 \\
-0.0023 & 0.0000 & 0.0029 \\
0.0000 & 0.0000 & 0.0000 \\
0.0000 & 0.0000 & 0.0000
\end{bmatrix}
\]

The sliding surfaces for the SMC approaches are defined by the switching matrices

\[
\begin{bmatrix}
-1.2597 & -0.1860 & 2.9246 & 0.8573 & 0.9801 \\
0.2883 & -1.2136 & 7.5108 & -0.1757 & 0.5020 \\
0.2341 & -0.3041 & -4.6723 & -1.1960 & -0.0149 \\
0.0000 & 0.0000 & 1.0000 & 0.0000 & 0.0000 \\
0.0000 & -1.0000 & 0.0000 & 8.0000 & 0.0000
\end{bmatrix}
\]

\[
A_m = \begin{bmatrix}
1.2597 & 2.1593 & -0.9801 \\
-0.2883 & 8.6712 & -0.5020 \\
-0.2341 & 3.3250 & 0.0149 \\
0.0000 & 0.0000 & 0.0000 \\
0.0000 & 0.0000 & 0.0000
\end{bmatrix}
\]

The simulation results for both SMC approaches are shown in Figures 3 to 6.

![Figure 3: system output (blue) and reference for the classical sliding mode control.](image-url)
Figure 4: Input control forces for classical sliding mode approach.

Figure 5: System output (blue) and reference for the unit vector sliding mode control.
VI. Conclusion

In this paper the authors presented two approaches for the design of MIMO Sliding Mode Controllers for the navigation of the AURORA Airship in the longitudinal mode. The bounded stability of the system is proved and the results are illustrated through a simulation example where the airship is submitted to a large variation in airspeed.

The results show that both approaches are strong and robust tool for the design of a single global control scheme for Unmanned Vehicles. The strong points of the SMC approach are the simplicity and easy of calculation of the control law, and its robustness to the unmodeled dynamics and perturbations. The main drawbacks are the possible arise of chattering in the control actuation, and the difficulty of adjust or tuning of the switching gains $\eta$ and $\rho$. In the future, an optimization approach will be proposed so that the tuning of the switching gains will be obtained as the solution of a nonlinear programming problem.

The inclusion of a model reference showed up to be a powerful strategy to minimize the errors as it generates best command signals. Although this technique is present only in the unit vector approach, it can be used by the classical sliding mode control approach with minor modifications of the switching matrix and the control law.

Further developments are necessary prior to flight tests, that are: (i) possible inclusion of adaptive gains or estimators to widen the operational airspeed to higher values; (ii) estimation of the model uncertainty for which the global stability is assured, that means the calculation of a robustness measure of the controller; (iii) extension to the hovering (zero groundspeed) case, that is a regulation problem; (iv) extension to the lateral mode control.
The nonlinear control design is the main subject of our present works, and the better approach among Sliding Mode Control and Backstepping will be selected in the future for the airship onboard control and navigation system.

Acknowledgments
The present work was sponsored by the Brazilian agencies Fapesp under grant n. 04/13467-5, and CNPq under grants n. 382739/2005-1, and n. 4907 69/2006-3.

References


