Robust Nonlinear Control of a Buoyancy-Driven Airship System Using Backstepping Integral Sliding Mode Control

Maziyah Mat-Noh, M. R. Arshad, and Rosmiwati Mohd-Mokhtar

Abstract This paper presents the development of nonlinear robust control based on backstepping and sliding mode control system to control a longitudinal plane of a new concept of airship. Nature of autonomous airship is non-rigid body, very nonlinear and therefore control strategy can be used to accommodate the nonlinearities in the airship model. The performance of the proposed controller is simulated using MATLAB/Simulink software which tested for nominal system, system with external disturbance and system with parameter variation to evaluate its robustness against external disturbance and parameter variations. The controller is designed for the gliding path from 10° downward to 10° upward. The performance of proposed controller is compared against the performance of backstepping sliding mode control and integral sliding mode control in terms of chattering reduction and steady state error. The simulation results have shown that the proposed controller has improved the output tracking performance around 25% better as compared to lowest performance of integral sliding mode and the undesired chattering in control input and sliding surface has been reduced almost 100%.

Keywords Buoyancy-driven airship · Longitudinal plane · Backstepping · Integral sliding mode control

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K. Isa et al. (eds.), *Proceedings of the 12th National Technical Seminar on Unmanned System Technology 2020*, Lecture Notes in Electrical Engineering 770,
https://doi.org/10.1007/978-981-16-2406-3_15

1 Introduction

A great attention was given in utilizing unmanned aerial vehicles for various applications such as surveillance, advertising, monitoring, inspection and explorations since its appearances in last fifty years ago. Many autonomous airships have been designed and developed. The summary of the developed autonomous airships is depicted in Table 1.

The buoyancy-driven airship works similar to underwater glider where it uses internal movable masses and a mass-adjustable internal air bladder to move forward. This concept of airship was introduced by R. Purandare in 2007 [2]. Later a few works were done based on the concept presented R. Purandare such as [3–5].

The airship is categorized as multi-input–multi-output nonlinear system. There are many issues in controlling the motion of the airship such as the airship is underactuated system, highly nonlinear, time-varying dynamic behaviour in nature, uncertainties in aerodynamic coefficients, and also disturbances by wind [6, 7].

Various control strategies have been developed to control the motion of autonomous airships begins from proportional-integral-derivative (PID) control, optimal control, robust control and also intelligent control. PID control have been proposed in [8–11]. De Paiva et al. [8] had proposed the PID control to control the semi-autonomous airship. Two types of PID schemes were used to control three different parameters. Full PID was used to control the longitudinal velocity acting on the thrusters, two proportional-derivative (PD) controllers to control the altitude and heading. In [9] Azhinheira et al. proposed PD controller which designed based on full dynamic model of the airship for hovering control. Later in 2010, Saiki et al. [10] also proposed PID control for altitude and pitching control for motion in longitudinal plane. Song et al. in [11] proposed three PID controllers which were derived using linearised model to control propulsion, elevator and rudder of the airship. The optimal control, linear quadratic regulator was proposed in [12] to control the airship waypoint navigation. The performance of the LQR was compared to sequential loop controller (SCL) where LQR demonstrated better results in most controlled parameters. Later in 2009, Wu et al. also proposed LQR to control the vertical plane of the buoyancy driven airship [3].

Backstepping is known as systematics and recursive design methodology was proposed in [13–15]. In [13], backstepping was designed for hovering control. The backstepping control law was designed for the airship which its dynamics was derived using a quaternion formulation. The controller was tested under wind and turbulent conditions to evaluate the effectiveness of the proposed controller. E. De Paiva et al. in [14] did comparison study to compare the performance of dynamic inversion, backstepping and sliding mode control (SMC) where the backstepping control able to track a complete mission of airship motion which is vertical take-off, path tracking, hovering, and vertical landing. In 2014, Zhang et al. [15] proposed the backstepping control where the control law was designed based the cascaded structure which consists of guidance control loop, attitude control loop and velocity control loop. Pereira in [16] proposed sliding mode control (SMC) to control longitudinal plane

Table 1 Summary of airship development [1]

Designer	Model	Special features	Max. altitude (m)	Max. speed (mph)	Country
ATG/WorldSkyCat	Skycat-20	VTOL and cargo aircraft	3000	97	UK
Sky-Hook Boeing	SkyHook JHL-40	Heavy lift four rotor and 40-ton lifting capacity	N/A	80	Canada/US
Lockheed Martin	HAA	Solar-powered, high altitude, unmanned, and un-tethered	18,000	28	US
Techsphere Systems International	SA-60	Spherical shape and low altitude	3000	35	US
Southwest Research Institute	HiSentinel Airship	Stratospheric and solar-powered	>22,000	N/A	US
21st Century Airship Inc.	N/A	Spherical shape	Low altitude	35	Canada
Millennium Airship Inc.	SkyFreighter	Hybrid, heavy lift, and VTOL	6000	80	Canada/US
Ohio Airships Inc.	DynaLifter PSC-3	Winged hybrid, VTOL, and heavy lift	3000	115	US
Zeppelin Luftschifftechnik Gmbh	Zeppelin LZ NT-07	Semi-rigid, internal rigid framework consisting of carbon fiber triangular frames and aluminium members	2500	81	Germany
LTA Corporation	Alize 50	Lenticular shape, semi-rigid, and VTOL	2000	81	France
AEROS	Aeroscraft ML866 model	Control of static heaviness, heavy lift, and VTOL	3000	115	US
Northrop Grumman/Airship Industries	N/A	Long endurance and multi-intelligence	6000	N/A	US/UK

of the airship. The SMC control law was designed based on conventional SMC and boundary layer SMC where boundary layer SMC demonstrated better performance than conventional SMC.

Many researchers proposed the control law based on integration of different techniques. Hygounenc and Souères [17] proposed the integration of backstepping control and sliding mode control strategies to control the conventional autonomous airship for very small perturbations. With the assumption allows the motion equation of airship to be decomposed into lateral and vertical planes, thus the controller can be designed separately for each plane. The controller was designed in two phases which is the transient longitudinal tracking and lateral path following for take-off and landing. After more than decade, the same method was proposed by Yang et al. in [7] for application in autonomous airship named "ZY-1" for poisoning control. Recently Pavia et al. proposed a method called unified backstepping SMC for positioning and trajectory tracking of autonomous airship.

Chen in [18] proposed adaptive backstepping SMC for tracking control of stratospheric airship which was simulated under influence of external disturbance and parametric uncertainties. Guo and Zhou proposed adaptive fuzzy sliding mode control (AFSMC) to control the lateral path of the airship. The same approach also proposed by Y. Yang et al. in [19] to control the position of the autonomous airship. The fuzzy logic was used to approximate the nonlinear parameters of the airship. In 2019, Zhou et al. [20, 21] proposed adaptive backstepping control for station-keeping control where in [20] a nonlinear disturbance observer was used to estimate the angular velocities of the attack and sideslip. However in [21] the fuzzy logic was used to estimate the model uncertainties. Wang et al. proposed the adaptive sliding mode control where the neuro-fuzzy was detect and isolate the fault of the sensor. Recently De Pavia et al. [22] and Shi et al. [23] proposed controller design backstepping and sliding mode control for tracking performance of autonomous airship.

The aim of this paper is to propose a robust nonlinear control strategy based on backstepping and integral sliding control (ISMC) which will be implemented in longitudinal plane of buoyancy-driven autonomous airship. The new control strategy is expected to improve the performance of the tested system. The combination of two control strategies is considered new with regards to control the longitudinal plane of buoyancy-driven autonomous airship system application and become the contribution of this paper. Moreover, the performance of the proposed controller will be compared to the performance of ISMC alone and backstepping SMC (BSMC).

This paper is organised as follows. In airship model section discusses the mathematical model of the longitudinal plane of the buoyancy-driven airship. The detail derivation of control for the proposed controller is discussed in controller design section. The results are discussed in results and discussion section. Finally, the paper is concluded in conclusion section.

2 Buoyancy-Driven Autonomous Airship Model

This section discusses the buoyancy-driven autonomous airship model. The mathematical model of airship system is adopted from Wu's works. The detail derivation of mathematical model can be found in [1]. The study only involves longitudinal plane which control the pitch angle and net buoyancy. The airship is driven using internal mass placed on the sliding track moves along x-axis. The definition of airship parameters is depicted in Table 2.

The motion equation of longitudinal of a buoyancy-driven autonomous airship is written in Eqs. (1)–(8).

$$\dot{\theta}_{as} = \Omega_{2as} \tag{1}$$

$$\dot{\Omega}_{2\mathrm{as}} = T_1 H_1 + T_2 H_2 - T_1 r_{p3as} u_1 \tag{2}$$

$$\dot{v}_{1as} = \frac{H_3}{m_1} - \frac{1}{m_1} u_1 \tag{3}$$

$$\dot{v}_{3as} = T_2 H_1 + T_3 H_2 - T_2 r_{p3as} u_1 \tag{4}$$

$$\dot{r}_{p1as} = \dot{r}_{p1as} \tag{5}$$

$$\ddot{r}_{p1as} = -\frac{H_3}{m_{1as}} - r_{p3as}(T_1 H_1 + T_2 H_2) + \left(\frac{1}{\bar{m}} + \frac{1}{m_1} + T_1 r_{p3as}^2\right) u_1 \tag{6}$$

$$\dot{P}_{p1as} = u_1 \tag{7}$$

$$\dot{m}_{bl} = u_{bl} \tag{8}$$

where

Table 2 Airship parameter definition

Parameter	Definition
θ_{as}	Pitch angle
Ω_{2as}	Pitch rate
v_{1as}	Surge velocity
v_{3as}	Heave velocity
r_{p1as}	Internal movable mass position in x-axis
$\dot{r}_{p1as}$	Internal movable mass velocity
m_{bl}	Bladder point mass

$$T_1 = \frac{m_{3as} + \bar{m}}{J_{2as}(m_{3as} + \bar{m}) + \bar{m}m_{3as}r_{p1as}^2}$$
$$T_2 = \frac{\bar{m}r_{p1as}}{J_{2as}(m_{3as} + \bar{m}) + \bar{m}m_{3as}r_{p1as}^2}$$
$$T_3 = \frac{J_{2as} + \bar{m}r_{p1as}^2}{J_{2as}(m_{3as} + \bar{m}) + \bar{m}m_{3as}r_{p1as}^2}$$

$$\begin{aligned}
H_1 &= (m_{3as} - m_{1as})v_{3as} - \bar{m}g\left(r_{p1as}\cos\theta_{as} + r_{p3as}\sin\theta_{as}\right) \\
&\quad - \left(r_{p1as}P_{p1as} + r_{p3as}\bar{m}\left(v_3 - r_{p1as}\Omega_{2as}\right)\right)\Omega_2 + M_a \\
&\quad + \bar{m}r_{p1as}\Omega_{2as}\left(v_{1as} - r_{p3as}\Omega_{2as}\right) - r_{p1as}\Omega_{2as}P_{p1as} \\
H_2 &= m_{1as}v_{1as}\Omega_{2as} + P_{p1as}\Omega_{2as} + m_0 g\cos\theta_{as} - Z_a\cos\alpha \\
&\quad - X_a\sin\alpha - \bar{m}\Omega_{2as}\left(v_{1as} - r_{p3as}\Omega_{2as}\right) + P_{p1as}\Omega_{2as} \\
H_3 &= m_{3as}v_{3as}\Omega_2 - \bar{m}\left(v_{3as} - r_{p1as}\Omega_{2as}\right)\Omega_{2as} - m_0 g\sin\theta_{as} \\
&\quad + Z_a\sin\alpha - X_a\cos\alpha
\end{aligned}$$

The input and state vectors are written in Eqs. (9) and (10) respectively.

$$\begin{aligned}
x &= [x_1\ x_2\ x_3\ x_4\ x_5\ x_6\ x_7\ x_8]^T \\
&= \left[\theta_{as}\ \Omega_2\ v_{1as}\ v_{3as}\ r_{p1as}\ \dot{r}_{p1as}\ P_{p1as}\ m_{bl}\right]^T
\end{aligned} \tag{9}$$

$$u = [\mathrm{u}_1\ u_{\mathrm{bl}}]^T \tag{10}$$

The airship system is under-actuated, therefore in this study only two parameters are considered which are pitch angle, θ_{as} and net buoyancy, m_0. The controlled parameter equations are written in Eqs. (11) and (12). The net buoyancy is indirectly controlled via the air bladder mass, m_{bl}.

$$y_1 = x_1 = \theta \tag{11}$$

$$y_2 = m_0 = m_h + \bar{m} + m_{bl} - m \tag{12}$$

where: $\bar{m}$ = Internal movable mass and m is airship displaced air mass.

3 Controller Design

This section presents the controller design methodology. The proposed controller, BISMC is designed based on the integration of backstepping and integral SMC. To evaluate the performance of the proposed controller two other controllers will be designed that are integral SMC and backstepping SMC. However, in this paper the derivation of control law only shown for BISMC. The detail derivation is ISMC and BSMC can be found in [24, 25]. All the controllers are designed for the flight path angle from 10º downward to 10º upward.

3.1 Problem Formulation of the Longitudinal Plane

This section presents the formulation for tracking problem the longitudinal plane of an airship system. Eqs. (1)–(8) are written into general nonlinear equation in Eqs. (13) and (14).

$$\dot{x} = f(x, t) + g(x, t)u + \delta(x, t) \tag{13}$$

$$y = b(x, t) \tag{14}$$

where, $x \in R^n$, $u \in R^m$ and $b \in R^p$ are the state, input and output vectors. $\delta(x, t)$ is the bounded matched perturbations which is bounded with a known norm upper bound, $\rho(x, t)$ as written in Eq. (15).

$$|\delta(x, t)| \leq |\rho(x, t)| \tag{15}$$

For simplicity, following assumptions are made:

Assumption 1 Consider the system in Eq. (13) is rewritten in n-th order system and in the form that is suitable for controller algorithms as written in Eq. (16)

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= x_3 \\ &\vdots \\ \dot{x}_k &= \varphi_k(x, t) + g_k(x, t)u_i + \delta_k(x, t) \\ &= \chi_k(x, u_i, t) + u_i + \delta_k(x, t) \end{aligned} \tag{16}$$

where $\chi_k(x, u_i, t) = f_k(x, t) + (g_k(x, t) - 1)u_i$, $k = 1, 2, 3, \ldots .n$, and $i = 1, 2, 3, \ldots p$. Equation (16) is known as General Global Controller Canonical Form (GGCCF). Detail explanation can be found in [26]. The system without perturbation is defined when $\delta_k(x, t) = 0$.

Assumption 2 The system in Eq. (16) is minimum phase when zero dynamic $\chi_k(0, u_i, t) = 0$ is uniformly asymptotically stable.

The system is divided into two subsystems which are pitch angle control subsystem and net buoyancy subsystem as written in Eqs. (17) and (18) respectively.

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = f_2(x,t) - g_2(x,t)u_1 - g_2(x,t)\delta_2(x,t) \tag{17}$$

$$\dot{x}_8 = u_{\text{bl}} + \delta_8(x,t) \tag{18}$$

The outline of formulation is for the tracking problems. The output errors are defined in Eqs. (19) and (20).

$$e_1 = x_1 - x_{1d} \tag{19}$$

$$e_8 = x_8 - x_{8d} \tag{20}$$

3.2 Backstepping Integral Sliding Mode Control (BISMC)

The BISMC control is defined based on ISMC control law as was proposed by Utkin and Shi [27]. The ISMC is a method where the sliding surface is enforced from the beginning, thus the reaching phase is eliminated. The control law of BISMC is defined in Eqs. (21) and (22).

$$u_{1BISMC} = u_{10} + u_{11} \tag{21}$$

$$u_{blBISMC} = u_{bl0} + u_{bl1} \tag{22}$$

where

u_{10} and u_{bl0}: The nominal controls that stabilize the system without perturbation (i.e. $\delta(x,t) = 0$)

u_{11} and u_{bl1}: Nonlinear (discontinuous) control law discontinuous control in nature that are derived by backstepping for perturbation rejection, $\delta_k(x,t)$.

Design of Nominal Control (u_{10} and u_{bl0})

u_{10} and u_{bl0} are defined using pole-placement method. The ideal control is defined when $\chi_2(x,u_1,t)$, $g_2\delta_2(x,t)$ and $\delta_8(x,t)$ are set to zero (i.e. system without perturbation). Equations (17) and (18) are rewritten in form of Eq. (16) as written in Eqs. (23) and (24).

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = \chi_2(x,\tilde{u}_1,t) - u_1 - g_2\delta_2(x,t) \tag{23}$$

$$\dot{x}_8 = u_{\mathrm{bl}} + \delta_8(x, t) \tag{24}$$

The system in Eq. (23) is written in state-space form

$$\dot{x} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ -1 \end{bmatrix} u_{10} \tag{25}$$

Using pole-placement method, u_{10} is defined as

$$u_{10} = -(-k_{11}e_1 - k_{12}e_2) = k_{11}e_1 + k_{12}e_2 \tag{26}$$

Similarly, for the system in Eq. (24), the u_{bl0} is defined in Eq. (27). The difference is that the subsystem (24) is a relative degree of one system.

$$u_{bl0} = -k_{21}e_8 \tag{27}$$

where $e_2 = \dot{e}_1 = x_2 - \dot{x}_{1d}$ and k_{11}, k_{12} and k_{21} are the positive constants.

Design of Nonlinear Control (u_{11} and u_{bl1})
Design on nonlinear control is explained in following steps.

Step 1: Nonlinear control formulation for system in Eq. (23).

(a) The tracking error and its derivative is defined in Eqs. (28) and (29)

$$e_1 = x_1 - x_{1d} \tag{28}$$

$$\dot{e}_1 = \dot{x}_1 - \dot{x}_{1d} = x_2 - \dot{x}_{1d} \tag{29}$$

(b) Define the Lyapunov function and its derivative

$$V_1(e_1) = \frac{1}{2} e_1^T e_1 \tag{30}$$

$$\dot{V}_1(e_1) = e_1^T \dot{e}_1 = e_1^T (x_2 - \dot{x}_{1d}) \tag{31}$$

x_2 is viewed as a virtual control and the desired virtual control known as stabilizing function is defined as

$$\alpha_1 = -K_{11}e_1 + \dot{x}_{1d} \tag{32}$$

where K_{11} is a positive constant. Then Eq. (31) becomes

$$\dot{V}_1 = e_1^T(-K_{i1}e_1 + \dot{x}_d - \dot{x}_d) = -K_{i1}e_1^T e_1 < 0 \tag{33}$$

(c) Define the sliding surface

$$s_1 = s_{10} + z_1 \tag{34}$$

where s_{10} a conventional SMC that is defined based on backstepping control strategy as written in Eq. (35) and z_i is an integral term that can be determined.

$$s_{10} = x_2 - \alpha_1 \tag{35}$$

Substituted Eq. (35) into Eq. (34) and rearranged to obtain Eq. (36)

$$x_2 = s_1 + \alpha_1 - z_1 \tag{36}$$

The derivative of sliding surface is written as

$$\begin{aligned}\dot{s}_1 &= \dot{s}_{10} + \dot{z}_1 = \dot{x}_2 - \dot{\alpha}_1 + \dot{z}_1 \\ &= \chi_2(x, u_1, t) + (u_{10} + u_{11}) + g_2\delta_2(x, t) + K_{11}\dot{e}_1 - \ddot{x}_{1d} + \dot{z}_i\end{aligned} \tag{37}$$

The time derivative of integral term is defined as

$$\dot{z}_1 = -u_{10} - K_{11}\dot{e}_1 + \ddot{x}_{1d} \tag{38}$$

(d) Define the augmented Lyapunov function and derivative as

$$V_2(e_1, s_1) = \frac{1}{2}(e_1^2 + s_1^2) \tag{39}$$

$$\dot{V}_2(e_1, s_1) = e_1\dot{e}_1 + s_1\dot{s}_1 \tag{40}$$

Therefore, the equivalent control, u_{11eq} is chosen such that the time derivative of augmented Lyapunov function in Eq. (40) is negative definite and is defined as

$$u_{11eq} = -\frac{1}{g_2}(f_2(x, t) + (g_2 - 1)u_{10} + K_{12}s_1 + \delta_2(x, t)) \tag{41}$$

the reachability condition is defined as

$$u_{11dis} = -M_1 sign(s_1) \tag{42}$$

Step 2: Nonlinear control formulation for system in Eq. (24)

(a) Define the sliding surface and its time derivative based on first order backstepping as

$$s_2 = s_{20} + z_2 = \mathrm{x}_8 - \mathrm{x}_{8\mathrm{d}} + \mathrm{z}_2 \tag{43}$$

$$\dot{s}_2 = \dot{x}_8 - \dot{x}_{8d} + \dot{z}_2 = u_{bl} + \delta_8(x,t) + \dot{z}_2 = u_{bl0} + u_{bl1} + \delta_8(x,t) + \dot{z}_2 \tag{44}$$

Derivative integral is chosen as

$$\dot{z}_2 = -u_{bl0} \tag{45}$$

(b) The Lyapunov function and its derivative is defined as

$$V_3(s_2) = \frac{1}{2}s_2^2 \tag{46}$$

$$\dot{V}_3(s_2) = s_2\dot{s}_2 \tag{47}$$

The equivalent and reachability condition are defined as

$$u_{bl1eq} = -K_{21}s_2 - \delta_8(x,t) \tag{48}$$

$$u_{bl1dis} = -M_2 sign(s_2) \tag{49}$$

Step 3: The overall control law for controlling pitch and net buoyancy is defined as

$$u_{1BISMC} = k_{11}e_1 + k_{12}e_2 - \frac{1}{g_2}\{f_2(x,t) + (g_2 - 1)u_{10} + K_{12}s_1 + \delta_2(x,t)\} - M_1 sign(s_1) \tag{50}$$

$$u_{blISMC} = -k_{21}e_8 - K_{21}s_2 - \delta_8(x,t) - M_2 sign(s_2) \tag{51}$$

3.3 Stability Analysis

This section presents the stability analysis of the proposed controller. The importance of stability analysis is to ensure the controlled parameters are stabilized at the desired value. Therefore, the Lyapunov stability theorem is used to ensure sliding mode and output convergence as explained in the following.

Theorem *Consider the nonlinear systems in Eqs.* (30) *and* (24) *subjected to bounded uncertainty in Eq.* (15) *with Assumptions* 1 *and* 2*. If the sliding manifolds* (s_1, s_2) *as written in Eqs.* (34) *and* (43)*, and the discontinuous controls* (u_{11dis}, u_{bl1dis}) *as written in Eqs.* (42) *and* (49)*, then the convergence conditions are satisfied.*

Proof Consider the Lyapunov functions in Eqs. (39) and (46)

$$V_1(e_1, s_1) = \frac{1}{2}(e_1^2 + s_1^2) \tag{52}$$

$$V_3(s_2) = \frac{1}{2}s_2^2 \tag{53}$$

The time derivative of the Lyapunov functions together with Eqs. (29), (37) and (44) yields

$$\begin{aligned}\dot{V}_1(e_1, s_1) &= e_1\dot{e}_1 + s_1\dot{s}_1 \\ &= e_1(x_2 - \dot{x}_{1d}) + s_1\{f_2(x,t) \\ &\quad -g_2(x,t)u_1 + g_2(x,t)\delta_2(x,t) + K_{11}\dot{e}_1 - \ddot{x}_{1d}\} \\ &= e_1(s_1 - K_{11}e_1) + s_1\{f_2(x,t) - g_2(x,t)u_1 \\ &\quad +g_2(x,t)\delta_2(x,t) + K_{11}\dot{e}_1 - \ddot{x}_{1d}\}\end{aligned} \tag{54}$$

$$\begin{aligned}\dot{V}_3(s_2) &= s_2\dot{s}_2 \\ &= u_{\mathrm{bl}} - \dot{x}_{8d} + \delta_8(x,t)\end{aligned} \tag{55}$$

Substitute Eq. (50) into Eq. (54), and Eq. (51) into Eq. (55). For stability

$$\begin{aligned}\dot{V}_1(e_1, s_1) &\le e_1(-K_{11}e_1) \\ &\quad + s_1(-K_{12}s_1 - M_1 sign(s_1)) < 0\end{aligned} \tag{56}$$

$$\dot{V}_2(s_2) \le s_2(-K_{21}s_2 - M_2 sign(s_2)) < 0 \tag{57}$$

where

$-K_{11}e_1^2 < 0$ for K_{11} is positive constant
$-K_{12}s_1^2 < 0$ for K_{12} is positive constant
$-K_{21}s_2^2 < 0$ for K_{21} is positive constant
M_1 and M_2 are positive constants.

4 Result and Discussion

This section presents all the results and discusses the performance of the proposed controller that was designed in previous section. The value of all parameters is adopted form Wu [1] as depicted in Tables 3 and 4. The simulation was done for nominal system (without perturbation), system with external disturbance and system with parameter variations to evaluate the robustness of the proposed controller.

Table 3 The parameter value of a buoyancy-driven airship [1]

Parameter	Value	Unit
Hull mass, m_s	269	kg
Internal sliding mass, $\bar{m}$	30	kg
Displaced air mass, m_{da}	382	kg
Mass, m_1, m_3	400, 500	kg
Inertia, J_2	8000	kg m^2
Lift coefficient, K_{LO}, K_L	0, 1.269	Ns/m
Drag coefficient, K_{DO}, K_D	0.059, 0.06	Ns/m
Moment coefficient, K_{MO}, K_M	0, 0.255	Ns/m

Table 4 Initial and desired values

Parameter	Initial	Desired
Pitch angle, θ_{as} (°)	−10	10
Surge velocity, v_{as1} (m/s)	3	–
Heave velocity, v_{as3} (m/s)	0.242	–
x-position of internal movable mass, r_{p1as} (m)	0.82	–
Bladder mass, m_{bl} (kg)	81	85
Access mass, m_0 (kg)	−2	2

The simulation results for nominal system are shown in Figs. 1, 2 and 3. All the controllers are able to stabilize at the desired value. The proposed controller able to stabilize at desired value within less than 10 s whereas ISMC and BSMC taking more than 10 s and BSMC gives highest steady error for pitch angle. All the controllers show similar performance for net buoyancy. The proposed controller provides smallest control effort and its sliding surface also provides smallest chattering effect.

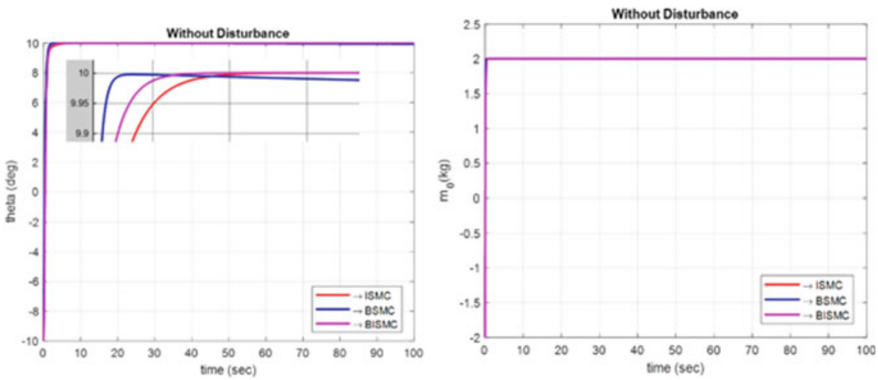

Fig. 1 Pitch angle θ and net buoyancy m_{em} (without disturbance)

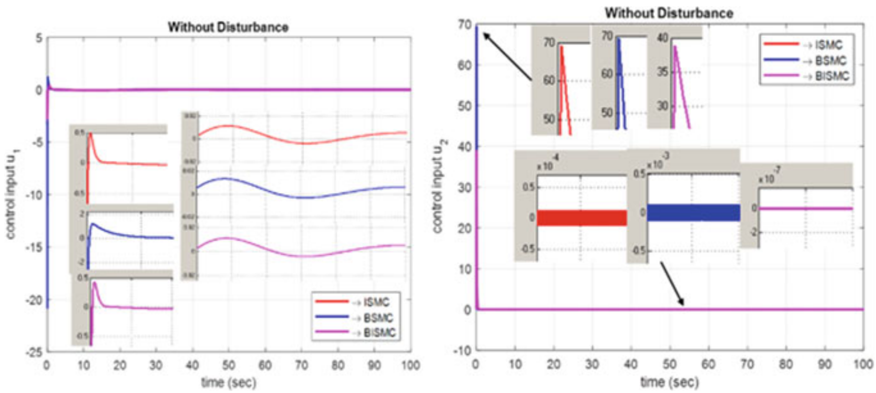

Fig. 2 Control input u_1 and u_{bl} (without disturbance)

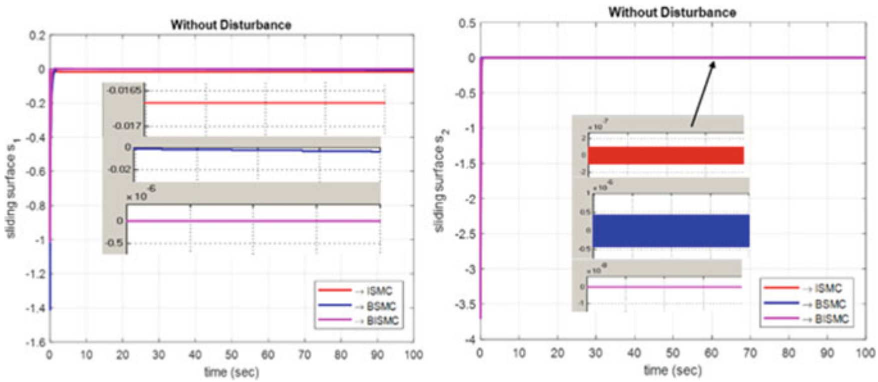

Fig. 3 Sliding surface s_1 and s_2 (without disturbance)

Figures 4, 5 and 6 show the simulation results for the system with external disturbance. An input matched external disturbance of $\delta_1(x, t) = 5x_1\sin(\pi t)$ and $\delta_5(x, t) = 0.1x_7\sin(\pi t)$ were induced to input channels 1 and 2 respectively. All the controllers are able to converge to the vicinity of the desired values with increase in steady-state error. The BIMC shows the smallest oscillation and BSMC shows the largest oscillation. The control effort of both inputs is increased and the chattering is also increased with proposed controller still able to provide lowest control effort and chattering effect.

The increment of 30% of the aerodynamic parameters are imposed at time = 50 s. The increment is shown in Table 5.

The responses for parameter variations are shown in Figs. 7, 8, and 9. All the controllers able to stabilize in the vicinity of desired values with BSMC shows the largest error in pitch angle. The proposed controller provides the lowest steady state error and lowest oscillation in sliding surface. All the increment parameters only

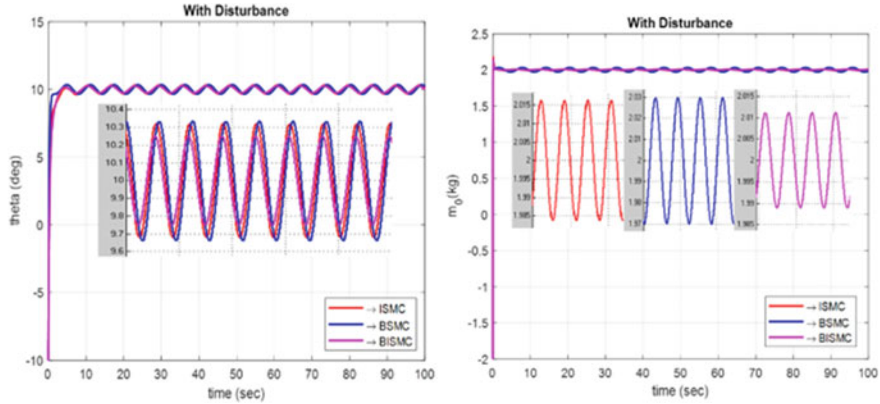

Fig. 4 Pitch angle θ and net buoyancy m_{em} (with disturbance)

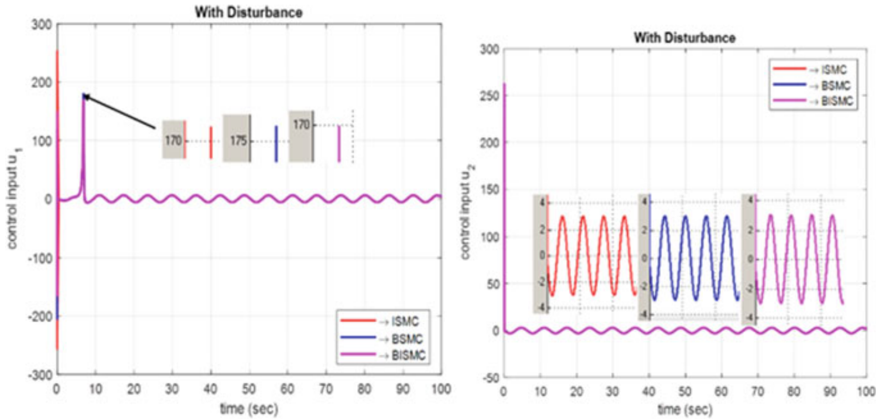

Fig. 5 Control input u_1 and u_{bl} (with disturbance)

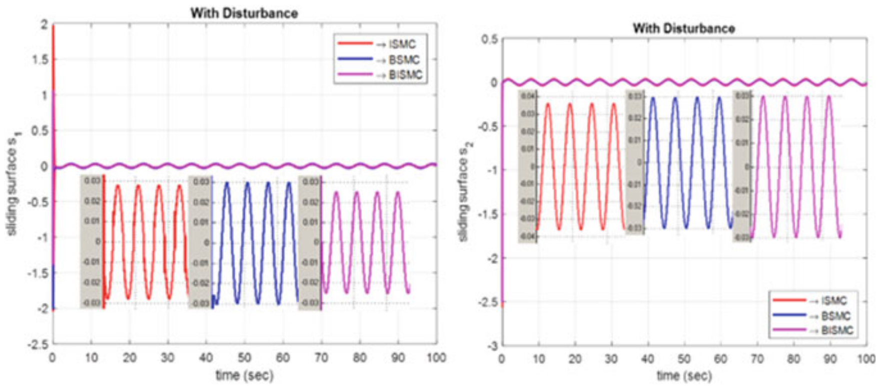

Fig. 6 Sliding surface s_1 and s_2 (with disturbance)

Table 5 Increment of parameters

Parameter	Nominal	Increased (300%)
m_1	400	520
m_3	500	650
J_2	8000	10,400
K_L	1.269	1.65
K_{LO}	0	0.30
K_D	0.016	0.02
K_{DO}	0.056	0.08
K_M	0	0.30
K_{MO}	0.255	0.33

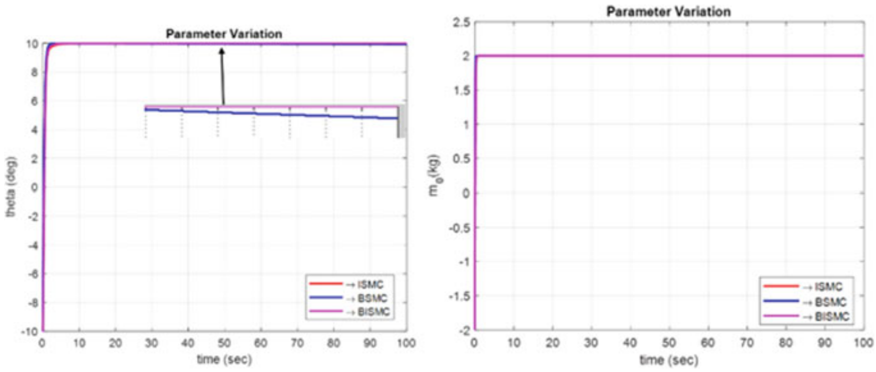

Fig. 7 Pitching angle θ and net buoyancy m_{em} (parameter variation)

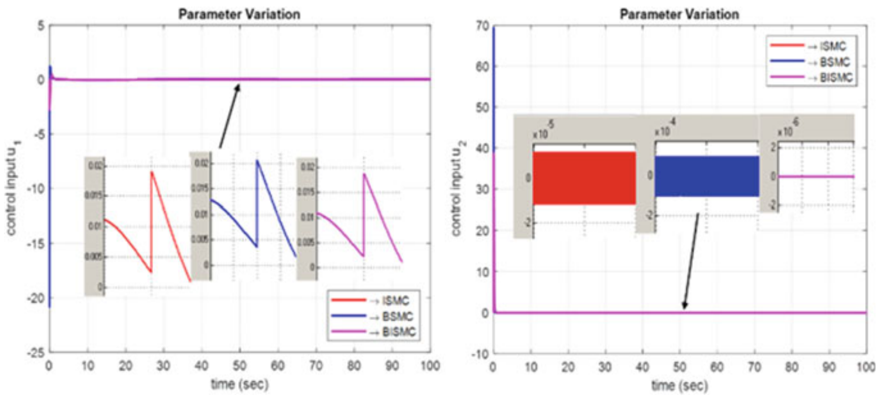

Fig. 8 Control input u_1 and u_{bl} (parameter variation)

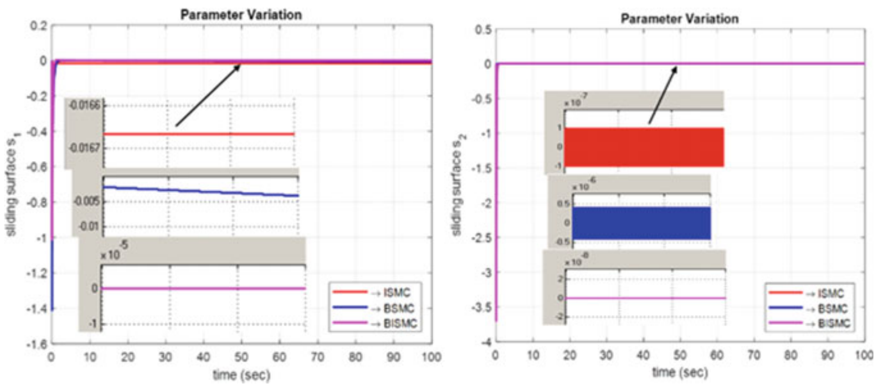

Fig. 9 Sliding surface s_1 and s_2 (parameter variation)

appear in equation related to pitch angle. Thus, the changes only effect the results related to pitch angle and the results for net buoyancy are remain unchanged same as nominal system.

5 Conclusion

The backstepping integral SMC (BISMC) has been successfully designed and implemented in longitudinal plane of the buoyancy-driven airship. The performance of BISMC has been compared to the performance of integral SMC (ISMC) and backstepping SMC (BSMC) in existence of external disturbance and uncertainties in aerodynamics. The numerical simulation result in previous section, a conclusion can be made that proposed controller able to provide improvement in reducing chattering phenomena in control input and sliding surface and improve transient performance as compared to ISMC and BSMC.

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