Design of a Multi-vector Thrust Aerostat with a Reconfigurable Control System

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Abstract: This paper presents an aerostat developed in the shape of an ellipsoid, which is a cross between a ball and a water droplet. This aerostat is equipped with four vectored thrusters. Its coefficient of forward drag is smaller than that of the spherical aerostat, and its lift efficiency is higher than that of the conventional airship. To allocate control among the multi-vector thrusters, a control system based on pseudo-inverse dynamics is designed. A reconfiguration strategy is also proposed to reallocate actuators in case of control actuator failure. Three diagonal weight matrices are combined to represent all possible failure situations occurred on vectored thruster, they make the reconfigurable controller more general. Based on simulation results under different fault situations, the reconfigurable control system performs more effectively than a normal control system in cases of actuator failure, even when more than one actuator fails. Reconfigurable ability of controller also validated in real flight experiment.

Keywords: aerostat, multi-vector thrusters, control allocation, pseudo-inverse dynamics, reconfiguration

1. Introduction

Among the different types of aerostats that have been developed, the most conventional types are the spherical and streamlined shapes [1]. Spherical aerostats have high lift efficiency and drag coefficients [2], whereas streamlined ones have lower drag coefficients in forward flight, and however, these streamlined aerostats are sensitive to crosswinds [3]. Several attempts have been made to alter the shape of the envelope [4, 5, 6, 7] and a frequently suggested configuration is the ellipsoid, which is a shape that is a cross between a ball and a water droplet and resembles either a “flying saucer” [6] or a “pumpkin” [7]. The ellipsoidal shape displays a reduced lateral profile in crosswinds and has a higher lift efficiency than an airship. Therefore, this shape is advantageous for a platform hovering at a given altitude. An ellipsoidal aerostat with a height-to-diameter ratio 0.6 is proposed in this paper; this aerostat shape is called elastic aerostat, and it stabilizes a super-pressured aerostat [8].

The elastica aerostat is finless, and equipped with four vectored thrusters offering 8 control degrees of freedom in order to manipulate 6 dynamic degrees of freedom, so the control system are over-actuated. In case of an actuator failures the remaining ones can be reconfigured by the control allocation without having to change the motion controller structure. A control allocation system implements a function that maps the desired control forces generated by the motion controller into the commands of the different actuators. Control allocation problems can be formulated as optimization problems, where the objective typically is to produce the specified generalized forces while minimizing the use of control effort (or power) subject to actuator rate and position constraints, power constraints as well as other operational constraints. The typical methods for control allocation include direct allocation algorithm [9, 10], daisy chaining algorithm [11, 12], pseudo-inverse algorithm [13, 14] and mathematical programming algorithm [15, 16]. Among these methods, the explicit solutions can be found and implemented efficiently only by using pseudo-inverse algorithm. And the weighted-pseudo-inverse method is further used to construct the reconfigurable system, where the weights are used for tuning purposes to prevent actuator oscillations or control position limits [17, 18].

A system based on pseudo-inverse dynamics has been designed to allocate control among the thrusters for this airship [19]. To reallocate the actuators in case of control actuator failure, a weighted pseudo-inverse based reconfiguration strategy is further developed. The weights taken here are indicating the actuator's working states: normal or failed. The reconfigurable control system can reallocate the actuators simply by modifying their individual weights; thus, system reconfiguration is quick. This system is also easy to implement due to the analytic solution of the pseudo-inverse based allocation. According to the simulation and experimental results under different fault situations, the reconfigurable control system performs more effectively than the normal control system in cases of actuator failure, even given more than one faulty control actuator.

2. Aerostat dynamics

2.1. Aerostat scheme

A real aerostat with a diameter of 6 m and a volume of 70 m³ is designed as shown in Fig. 1. The aerostat is equipped with four vectored thrusters, and the equipment tank is suspended under its body to increase pitch stability.

The shape advantages of this envelope can be evaluated by two parameters: drag coefficient and lift efficiency. Drag coefficient C_D is obtained when drag D is divided by reference surface $V^{2/3}$ (V : aerostat volume). Lift efficiency L_e is

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equivalent to the volume size per unit of surface area (S : aerostat surface area).

$$C_D = \frac{D}{V^{2/3}} \quad (1)$$

$$L_e = \frac{V}{S} \quad (2)$$

Fig. 1. Overall structure of the elastica aerostat

The differences in the shape features of the elastica aerostat from those of the other two aerostats are presented in Table 1. The height-to-diameter ratio is the basic feature to identify the envelope shape, accordingly they have different lift efficiency and drag coefficient with different height-to-diameter ratio. Given that the lift efficiency of a spherical aerostat is normalized as 1, then the lateral drag coefficient of the elastica aerostat is lower than that of streamlined airship, and its lift efficiency is higher. The forward and lateral drag coefficients of the elastica aerostat are also lower than those of a spherical aerostat.

Table 1. Shape features of three typical aerostats

Shapes Features	Spherical	Streamlined	Elastica
Height-to-diameter ratio	1	0.3	0.6
Lift efficiency	1	0.78	0.95
Forward drag coefficient	0.6	0.04	0.3
Lateral drag coefficient	0.6	1.26	0.3
Vertical drag coefficient	0.6	1.16	0.83

The elastic aerostat, which has four thrusters, has eight control inputs (i.e., the rotation speed and vectored angle of each thruster). Its position and attitude can be controlled independently and the redundant control system tolerates faults to a certain extent. Therefore, control must be allocated among the multi-vectored thrusters.

2.2. Dynamics model of the elastica aerostat

The dynamics of this aerostat are similar to those of a conventional airship. External forces and moments are induced by gravity, buoyancy, fluid inertia force, aerodynamics, and thrusters. Through force analysis, the following dynamics equation can be constructed in the body-fixed frame:

$$\mathbf{M} \begin{bmatrix} \dot{u}_b & \dot{v}_b & \dot{w}_b & \dot{p}_b & \dot{q}_b & \dot{r}_b \end{bmatrix}^T = \mathbf{F}_T + \mathbf{F}_{GB} + \mathbf{F}_A + \mathbf{F}_I \quad (3)$$

where $\mathbf{M}$ is the mass matrix; $\dot{u}_b$, $\dot{v}_b$, and $\dot{w}_b$ denote linear accelerations; $\dot{p}_b$, $\dot{q}_b$, and $\dot{r}_b$ represent the angular accelerations around the body frame; and the right-hand side of the equation corresponds to external forces and moments, including gravity and buoyancy $\mathbf{F}_{GB}$, aerodynamic force $\mathbf{F}_A$, coriolis force $\mathbf{F}_I$, and vectored thrust $\mathbf{F}_T$.

2.3. Decomposition of vectored thrusts

To control six-channel attitude and position, the elastica aerostat has four vectored thrusters with eight control variables. Control must therefore be allocated across multiple channels to synchronize it. The vectored angle of each propeller is denoted by $\mu_i (i=1,2,3,4)$, and the generated force is represented by $f_i (i=1,2,3,4)$. Amplitude of the thrust is determined by the rotational speed of the propeller and direction of the thrust is determined by the vectored angle. In the vectored-rotation plane, the vectored thrust can be decomposed into two orthogonal forces f_{iH} and f_{iV} : $f_{iH} = f_i \cdot \sin \mu$ and $f_{iV} = -f_i \cdot \cos \mu$ [19].

The body frame is established as the general frame used on quadrotor air vehicle (Fig. 2). The x-axis of the body-fixed frame is coincide with one of the four thruster. Orthogonal forces f_{iH} and f_{iV} can also be deconstructed into the body-fixed frame along the x-, y-, and z-axes.

Fig. 2. Decomposition of the horizontal thrusts in the body-fixed frame

Therefore, the six-dimensional thrusts and their moments in the body frame are deduced as follows:

$$\begin{aligned}
 F_{Tx} &= f_{2H} - f_{4H} \\
 F_{Ty} &= -f_{1H} + f_{3H} \\
 F_{Tz} &= -f_{1V} - f_{2V} - f_{3V} - f_{4V} \\
 M_{Tx} &= (f_{2V} - f_{4V})R_p \\
 M_{Ty} &= (-f_{1V} + f_{3V})R_p \\
 M_{Tz} &= -(f_{1H} + f_{2H} + f_{3H} + f_{4H})R_p
 \end{aligned} \tag{4}$$

The matrix form of Eq. (4) is written as

$$\begin{bmatrix} F_{Tx} \\ F_{Ty} \\ F_{Tz} \\ M_{Tx} \\ M_{Ty} \\ M_{Tz} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & -1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & R_p & 0 & -R_p \\ 0 & 0 & 0 & 0 & -R_p & 0 & R_p & 0 \\ R_p & R_p & R_p & R_p & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} f_{1H} \\ f_{2H} \\ f_{3H} \\ f_{4H} \\ f_{1V} \\ f_{2V} \\ f_{3V} \\ f_{4V} \end{bmatrix} \tag{5}$$

and

$$F_T = P \cdot F_{THV} \tag{6}$$

where $F_T = [F_{Tx}, F_{Ty}, F_{Tz}, M_{Tx}, M_{Ty}, M_{Tz}]^T$ denotes the forces of the direct action of the thrusters on the body; $F_{THV} = [f_{1H}, f_{2H}, f_{3H}, f_{4H}, f_{1V}, f_{2V}, f_{3V}, f_{4V}]^T$ indicates the forces of indirect action; and P represents the indirect control matrix.

$$P = \begin{bmatrix} 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & R_p & 0 & -R_p \\ 0 & 0 & 0 & 0 & -R_p & 0 & R_p & 0 \\ R_p & R_p & R_p & R_p & 0 & 0 & 0 & 0 \end{bmatrix}$$

3. Design of the reconfigurable control system

The vectored-thrust aerostats, such as the spherical or elastica aerostat, differ from the airship [20, 21, 22]. The elastica aerostat has an isotropic drag coefficient, lateral control capability, and independent control of position and attitude. Thus direct position control can be realized. The disturbance rejection ability of direct control is strong because of the direct position error tracking.

For this multi-vectored thrust aerostat, the control system is designed based on pseudo-inverse dynamics. Since the dynamic

inversion is explicitly defined in terms of the internal model, so it is sensitive to modeling errors. Two approaches have been proposed to desensitize dynamic inversion to onboard model error. One approach uses an adaptive method to adaptively regulate the plant inversion error [23, 24]. The other less complicated approach considered here is based on an incremental version of nonlinear dynamic inversion (NDI) [25]. Improved dynamic inversion approaches have been proposed to accommodate to the limits. An improved control allocator utilizing a multi-pass strategy minimizes both effectors rate and position [26]. The Redistributed pseudo-inverse method (RPI) is an alternative solution, in which all control inputs that violate their bounds in the pseudo-inverse solution are saturated and removed from the optimization [10]. General-weighted least-norm (GWLN) method was also proposed to effectively meet the multiple constraints [27]. So the dynamic inverse flight control system is ideal for aerostat since gain scheduling is avoided within the range of airspeed.

3.1. Normal Controller Design and Simulation

The normal controller was designed under normal actuator situation, that there is no failure occurred [19]. Following simulations are given to prove that the normal controller cannot work well in case of actuator failure. Here a position tracking is given, the current position is denoted by $P(0m, 0m, 0m)$, and the expected position is represented by $P_c(20m, 20m, 20m)$. The maximum thrust of each propeller is 20 N. Fig.3 shows the simulation results without actuator any failures, which indicate that the control method can accurately track position and that the actuators are constrained within their maximum positions.

Subsequently, the control system is tested under actuator failure. In this study, the vectored angle of thruster 1 stuck at zero position and simulation results are depicted in Fig.4. The position is ineffectively tracked, which suggests that the normal control system cannot compensate for actuator failure. Therefore, a reconfigurable control system must be developed to enforce flight reliability.

Fig. 3. Tracking results of the position of the normal controller

Fig. 4. Tracking results of the position of a normal controller when thruster 1 is stuck

3.2. Reconfigurable control allocation based on a weighted pseudo-inverse method

The reconfigurable flight control system is based on the normal controller designed in Ref.[19], with the weighted pseudo-inverse algorithm approach. The weighted pseudo-inverse method is combined with the direct position controller. On the strength of robustness of direct position controller, the control law remains unchanged, and the weights are varied corresponding to the actuator situation: normal or failed, and thus indicating rapid reconfiguration in case of any failure. For the general implementation of the allocation, three diagonal matrices of weights are adopted. Three kinds of weights are combined together to represent the all possible faults of vectored thruster: magnitude deficiency, vectored angle stuck and actuator failed.

The first weight matrix is $\mathbf{W}_1$, which denotes the state of every normal thruster. As a result, Eq. (6) is expanded to:

$$\mathbf{F}_T = \mathbf{P} \mathbf{W}_1 \mathbf{F}_{T_{HV}} \quad (7)$$

where $\mathbf{W}_1 = \text{diag}([e_1 w_{f1} \ e_2 w_{f2} \ e_3 w_{f3} \ e_4 w_{f4} \ e_1 w_{f1} \ e_2 w_{f2} \ e_3 w_{f3} \ e_4 w_{f4}])$; w_{fi} is thruster weight; and $w_{fi} = 1$ is the weight of the normal actuator. If $w_{fi} = 0$, the actuator encounters fault one and may either be stuck in a vectored angle or cause thrust deficiency. e_i is the weight of maximum thrust of each deficient thruster.

$$F_{T_{imaxf}} = e_i \cdot F_{T_{imax}} \quad (8)$$

where $F_{T_{imax}}$ is the maximum value of a normal actuator; and $F_{T_{imaxf}}$ is the real maximum thrust under thrust deficiency.

In a stuck fault, the trigonometric function matrix of a vectored angle must be separated from thruster amplitude. Thus, Eq. (6) is rewritten again as

$$\mathbf{F}_T = \mathbf{P} \mathbf{S} \mathbf{f} \quad (9)$$

where $\mathbf{f} = [f_1 \ f_2 \ f_3 \ f_4]^T$ and f_i represents thruster amplitude. In addition,

$$\mathbf{S} = \begin{bmatrix} \sin \mu_{10} & & & \\ & \sin \mu_{20} & & \\ & & \sin \mu_{30} & \\ & & & \sin \mu_{40} \\ -\cos \mu_{10} & & & \\ & -\cos \mu_{20} & & \\ & & -\cos \mu_{30} & \\ & & & -\cos \mu_{40} \end{bmatrix}$$

where μ_{i0} denotes the position at which the thruster is stuck.

In failure cases, the last two weight matrices are incorporated into Eq. (9) as

$$\mathbf{F}_T = \mathbf{P} \mathbf{W}_s \mathbf{S} \mathbf{W}_2 \mathbf{f} \quad (10)$$

where $\mathbf{W}_2 = \text{diag}([e_1(1-w_{f1}) \ e_2(1-w_{f2}) \ e_3(1-w_{f3}) \ e_4(1-w_{f4})])$ indicates the weight of the thruster as a result of any failure; $\mathbf{W}_s = \text{diag}([w_{\mu1} \ w_{\mu2} \ w_{\mu3} \ w_{\mu4} \ w_{\mu1} \ w_{\mu2} \ w_{\mu3} \ w_{\mu4}])$ denotes the weight of a stuck thruster; and $w_{\mu i}$ is the weight of the vectored angle. If $w_{fi} = 0$ and $w_{\mu i} = 1$, the failure is stuck at a certain vectored angle, but with normal thrust amplitude. If $w_{fi} = 0$ and $w_{\mu i} = 0$, the thruster has failed completely and no action can be taken.

Thus, total thrust force can be determined by:

$$\mathbf{F}_T = \mathbf{P} \mathbf{W}_1 \mathbf{F}_{T_{HV}} + \mathbf{P} \mathbf{W}_s \mathbf{S} \mathbf{W}_2 \mathbf{f} \quad (11)$$

The first item on the right side of the equation represents the contribution of normal thrusters, and the second item indicates the contribution of the failed actuators. By using the weight matrix $\mathbf{W}_1$, the thruster deficiency can be considered. By introducing the weight matrixes $\mathbf{W}_s$ and $\mathbf{W}_2$, the thruster stuck can be considered. By using the weight matrixes $\mathbf{W}_1$, $\mathbf{W}_2$ and $\mathbf{W}_s$, the failed thruster can be considered. In this controller the indirect action force $\mathbf{F}_{T_{HV}}$ in Eq. (6) is maintained, which guarantees the presence of the pseudo-inverse of constant matrixes $\mathbf{P} \mathbf{W}_1$ and $\mathbf{P} \mathbf{W}_s \mathbf{S} \mathbf{W}_2$ as long as the fault situations were given. So there always exists solution to the controller.

Table 2 shows the relationship of actuator failure with the weights.

Table 2. Actuator state and weights

Actuator State	Thruster i Normal	Thruster i Failed	Thruster i Stuck	Thruster i with Thrust Deficiency	Thruster i Stuck and with Thrust Deficiency
Weights	$w_{fi}=1$ $w_{\mu i}=0$ $e_i=1$	$w_{fi}=0$ $w_{\mu i}=0$ $e_i=0$	$w_{fi}=0$ $w_{\mu i}=1$ $e_i=1$	$w_{fi}=1$ $w_{\mu i}=0$ $e_i=c < 1$	$w_{fi}=0$ $w_{\mu i}=1$ $e_i=c < 1$

3.3. Design of the reconfigurable control system

Based on the normal control system [19], the proposed structure of reconfigurable control is rebuilt as depicted in Fig. 5. The redistributed pseudo-inverse technique is taken between the normal actuators and the actuators of any failure and the integral anti-windup scheme is also taken to handle the input saturation of every single actuator by introducing the feedback into the controller, and there is no significant performance degradation due to the integral anti-windup when there is no saturation in the system [28]. During reconfiguration, commanded force F_{Tc} is induced by the proportional-integral-derivative controller. The allocator then calculates force F_T' as generated by the normal actuators, reallocates residual force ΔF_{Tc} among the fault actuators, and induces compensation force F_T'' . The model of external fault detection produces the signal to change the weight of every thruster, the fault detection model is not designed in this paper, so the failures is defined in advance. In this study, Δf_n and Δf_f are the oversaturated forces of the normal and faulty actuators, respectively, and K_1 and K_2 are the coefficient matrices for anti-windup.

Fig.5. Reconfigurable system structure

The advantages of this controller over the normal controller in implementation is that it can be used in a general situation. In the control allocation, the normal actuators have the priority to the fault actuator in actuation to achieve better performance and less energy consumption. If the commanded force cannot be satisfied, the reconfigurable controller takes effect by changing its weights to adapt to the failure of fault actuators. All the possible failure situations can be implemented through weight setting and the system retains full controllability as long as the remaining actuators still have the actuation ability.

4. Simulation and experimental validation

4.1. Simulation under various failure events

The reconfigurable system is similarly simulated under various failure conditions. First, the same failure presented in Fig. 4 is applied, and the results are shown in Fig. 6. Because of taking the fault actuator state into the controller allocation, the aerostat with the reconfigurable system recovers the ability in 3-D position tracking, and the performance is not much different from that with the normal actuator situation. Furthermore, the following fault cases are simulated as well: where thrusters 1, 2 stuck at zero and thrusters 3,4 are normal (Fig. 7) and where thrusters 1 and 2 stuck at zero and thrusters 3,4 display a deficiency of 1/2 (Fig. 8). Comparing the Fig. 7 and Fig. 8, with the same fault actuators, the provided maximum thrust is decreased to half, then the response time is extended and initial attitude error is larger. Fig. 9 gives the results when thrusters 1 and 2 are totally failed and Fig. 10 gives the six channels control force error between the commanded control force F_{Tc} and the real control force $F_T' + F_T''$. In this fault case, the control force error is larger in the initial response because of the actuator saturation, when it reached the final position then the error diminished gradually as shown in Fig.10. Fig. 11 shows the results when thrusters 1 and 2 fail and thrusters 3,4 display a deficiency of 1/2, as compared with Fig.9, the provided maximum thrust is decreased to half, then the response time is extended and initial attitude error is enlarged. Fig.12 gives the results when thrusters 3 and 4 fail and Fig.13 shows the results of six channels control force error in this situation, the tracking results are poor in this situation and the control force error is big in the initial response and the error is expanded in the tracking phase, which cannot be recovered to zero in yaw and x,y direction, that means the basic x,y position and yaw control cannot be achieved because beyond the capacity of all actuators.

Fig. 6. Position control of the reconfigurable system when thruster 1 is stuck at zero

Fig. 7. Position control of the reconfigurable system when thrusters 1,2 are stuck at zero

Fig.8. Position control when thrusters 1 and 2 stuck at zero and thrusters 3,4 display a deficiency of 1/2

Fig. 9. Position control when thrusters 1 and 2 fail

Fig.10. Control force error when thrusters 1 and 2 fail

Fig.11. Position control when thrusters 1 and 2 fail and thrusters 3,4 display a deficiency of 1/2

Fig.12. Position control when thrusters 3 and 4 fail

Fig.13. Control force error when thrusters 3 and 4 fail

4.2. Position tracking for reconfiguration test

From the above simulations, we can see that the reconfigurable control system can adjust its allocation according to the real actuator situation. In general, it can tolerate two failed actuators. In this section horizontal position tracking experiments were conducted while thruster 4 is power off and stuck at the vectored angle of 180° , the position and the heading angle were controlled together, the initial point is (0,0) and the final position is (20,-20). The simulation results are shown in Fig.14. And the experimental results are shown in Fig.15. The experimental result is almost in agreement with the

simulation results. With the outside disturbance the actuator vectored angles are oscillated obviously in flight experiment and the real force magnitude is smaller than that in the ideal simulation. In case of two failed actuators the aerostat actuation ability is too weak to resist the wind, so further experimental validation should on the new developed aerostat with more strong actuators.

Fig.14. Simulation results in position tracking while thrusters 4 is power off

Fig.15. Experimental results in position tracking while thrusters 4 is power off

5. Conclusion

A multi-vector thrust aerostat equipped with four vectored thrusters is developed in this study. The direct position controller is combined with weighted pseudo-inverse method to design the reconfigurable controller. On the strength of robustness of direct position controller, the control law remains unchanged, and the weights are varied corresponding to the actuator situation, and thus indicating rapid reconfiguration among multi-vector thrusters. In the allocation structure, the normal actuators has the priority to the fault actuator in actuation to achieve better performance and less energy consumption. Three diagonal weight matrices are combined to represent all possible failure situations occurred on vectored thruster, such the reconfigurable controller is general.

Simulation findings under different failure situations indicate that the reconfigurable control system performs well in many fault cases, even when more than one actuator fails. The experimental result of one actuator failure is demonstrated. With the outside disturbance the actuator vectored angles are oscillated obviously in flight experiment and the real force magnitude is smaller than that in the ideal simulation. Further experimental validation should on the new developed aerostat with stronger actuators.

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