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Feasibility Studies on a High-Altitude Captive Lighter-Than-Air Platform System

Kazuhisa Chiba*
The University of Electro-Communications, Tokyo 182-8585, Japan

Shin Satori†and Ryuichi Mitsuhashi‡
Hokkaido University of Science, Sapporo 006-8585, Japan

Masahiko Onda§and Masaaki Sano¶
Sky Platform Technologies Co. Ltd., Tochigi 320-0855, Japan
and
Jun'ya Sasaki‖and Ryojiro Akiba**
Hokkaido Aerospace Science and Technology Incubation Center, Sapporo 001-0010, Japan

A station-keeping platform in the stratosphere can be a novel foothold toward space activities. If the platform is conformed as free-flight LTA vehicles, there are possibilities that they may be blown away by the atmospheric advection due to its free-flight nature. Therefore, mooring this type of platform to the ground by a cable will be much easier to hold it in position. This concept of a captive platform system looks somewhat similar to rockoon systems which provided remarkably good services for the space observation in the past days. Namely, application of a captive platform system to a rocket launch pad is well expected to realize a space transportation system of ample payload capacity with much frequent services. In addition, this newly conceived system will have a wide spectrum range of application fields such as agriculture, meteorology, communication, etc. However, several technical issues are identified to materialize such a captive stratospheric platform. In these studies, summary results are presented for each of these technical issue items regarding flight tests, tether system operation, and wireless communication experiment. Consequently, useful knowledge has been empirically acquired concerning the above issues in order to construct a captive LTA stratospheric platform.

I. Introduction

Realizing a firm lower-stratospheric lighter-than-air (LTA) platform will enable a foothold for wide-range space activities. Japan Aerospace Exploration Agency (JAXA) had carried out research and developments on free flight type LTA stratospheric platforms for several years in early 2000s. Although these activities were remained stranded due to unavailability of suitable thrust power units and their limited performances in high altitude environment, its objective validity is never lost. What should be noted here is that a stratospheric platform can be an ideal rocket launch pad for space transportation. A concept of a captive lower-stratospheric platform system is similar to rockoon systems[1] which provided remarkably successful services for space observations in the years of 1950's and 1960's.

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*Associate Professor. Senior Member AIAA.
†Professor. Member AIAA.
‡Professor.
§R&D Officer. Associate Fellow AIAA.
¶Research Manager.
‖Engineer.
**President. Member AIAA.

Stratospherically dwelling platforms have been considered to make useful launch pads in place of rockoon systems and to conform frequent space transport systems with higher loading capacity. For this reason, fixed-wing aircraft has been tried[2,3] since launching rockets from the lower stratosphere are believed to contribute to frequently performed transporting methods. Although upper limits of payload weight for presently available airplanes are more or less 100 [t], advantages of airplanes over rockoon systems resides in providing with initial kinetic energy by their near-sonic speeds in the lower stratosphere. However, there exist several technical issues such as rocket installation and separation to make full use of the above mentioned merits. In this sense, as this kinetic energy can be calculated as equivalent to at most 5 [km] of rockoon altitudes, a captive lower-stratospheric LTA platform system can also possibly take place of the airplanes' role.

Moreover, captive lower-stratospheric platform system can be applied to multidisciplinary domains such as agriculture[4], defense[5], meteorology[6], environmental sciences[7], telecommunication[8] and so on. As adverse effects by clouds can be as well ignored at over 10 [km] altitudes, this type of platform can be emphatically hoped as to lay a new useful bridge between space and the terrestrial ground. The advantageous points of a captive LTA lower-stratospheric platform system are that 1) thrust is not required for keeping a platform in position and 2) a platform can have only a tether rope to hold its position in the air. The tether cable can also be utilized for conveying payload, electric power, and for replenishing buoyant gas. In addition, the cargo carrying vehicle called a "climber" can ascent and descent along the tether cable as its guiding rope.

The goal of our studies is to embody a concept of a captive lower-stratospheric platform system conformed as an LTA hull and a tether rope as a new infrastructure. At the first step, hull geometries are conceptually designed. Since the hull will be membrane-made structure to realize minimal weight and dimension, its manufacturing methods and related issues should be clarified during these design phase. As this platform is moored, the kinetic behaviors of the total system under severe weather conditions should be analyzed in order to verify the system's availability[9]. This first step is basic research phase. As the second step, missions should be defined, and the required mission instruments with avionics and also climbers should be developed. This second step is for a practical manufacturing phase. For the third step, marketing and business model construction will be made in order to successfully implement the system into the market. This work is a somehow separate step from engineering works. The studies presented here deal with the above second step. In these studies, the afore-mentioned technical issues were analyzed and their results were presented. Namely, the first one is flight tests of captive hybrid LTA kite with a tether cable and its tether system operation. The second item is wireless communication tests for telecommunication between the stratosphere and the terrestrial ground.

II. Tether Cable Motion Analysis

A. Derivation of Governing Kinetic Equations

Firstly, governing equations are derived to describe behaviors of a captive lower-stratospheric platform system comprised with an LTA vehicle and a tether cable. The adopted coordinate system is shown in Fig. 1. A wind velocity vector $\boldsymbol{w}$ is defined in the x-y plane. $\boldsymbol{w}$ will load a drag against the tether cable. θ [deg] is defined as an elevation angle of the tether cable in its sectional plane. ϕ [deg] is an azimuthal angle of the wind direction in the x-y plane, which augments counterclockwise from the x axis.

A unit tangent vector for the tether cable $\boldsymbol{t}$ is described in the following equation.

$$\boldsymbol{t} = \frac{dx}{ds}\boldsymbol{i} + \frac{dy}{ds}\boldsymbol{j} + \frac{dz}{ds}\boldsymbol{k}. \tag{1}$$

Where, ds is denoted for an infinitesimal length of the tether cable. In this way, the following equations are geometrically acquired.

$$\begin{aligned} dx &= ds\cos\theta\cos\phi, \\ dy &= ds\cos\theta\sin\phi, \\ dz &= ds\sin\theta. \end{aligned} \tag{2}$$

Consequently, $\boldsymbol{t}$ is converted to the following equation.

$$\boldsymbol{t} = \cos\theta\cos\phi\boldsymbol{i} + \cos\theta\sin\phi\boldsymbol{j} + \sin\theta\boldsymbol{k}. \tag{3}$$

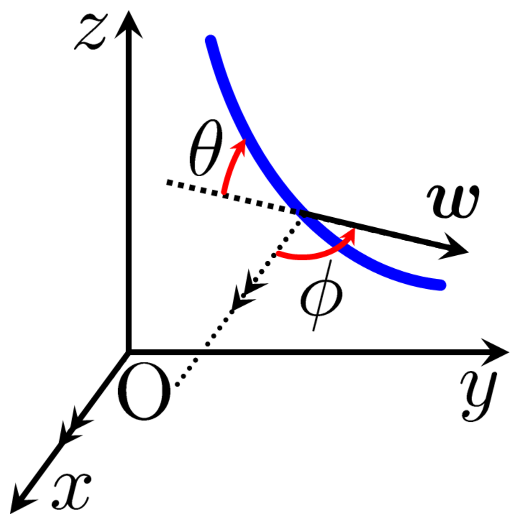


Figure 1. Coordinate system for behavioral analysis of the captive high-altitude platform system comprised with an LTA vehicle and a tether cable. Blue colored curve line symbolizes the tether cable.

In addition, tension T [N] which the tether cable incurs can be expressed by an elevation angle of the tether cable θ [deg], as the following.

$$\frac{\mathrm{d}T}{\mathrm{d}s} = D_{w_{xy}} \sin\theta \cos\theta - W \sin\theta, \tag{4}$$

$$-T\frac{\mathrm{d}\theta}{\mathrm{d}s} = D_{w_{xy}} \sin^2\theta + W \cos\theta, \tag{5}$$

where, $D_{w_{xy}}$ [N/km] is a drag of the tether cable for its unit length in the x-y plane due to wind blow. W [N/km] is a specific weight of the tether cable for its unit length. The governing equations are finally combined with Eqs. (2), (4), and (5), becoming the following.

$$\frac{\mathrm{d}}{\mathrm{d}z}\begin{bmatrix} T \\ \theta \\ x \\ y \\ s \end{bmatrix} = \begin{bmatrix} D_{w_{xy}} \cos\theta - W \\ -\dfrac{D_{w_{xy}} \sin\theta + W \cot\theta}{T} \\ \cot\theta\cos\phi \\ \cot\theta\sin\phi \\ \csc\theta \end{bmatrix}, \tag{6}$$

where, $D_{w_{xy}}$ is defined as follows;

$$D_{w_{xy}} = C_d^{(\mathrm{tether})} \cdot \frac{1}{2}\rho_{\mathrm{air}}(z) w^2(z) \cdot S_{\mathrm{ref}}^{(\mathrm{tether})}, \tag{7}$$

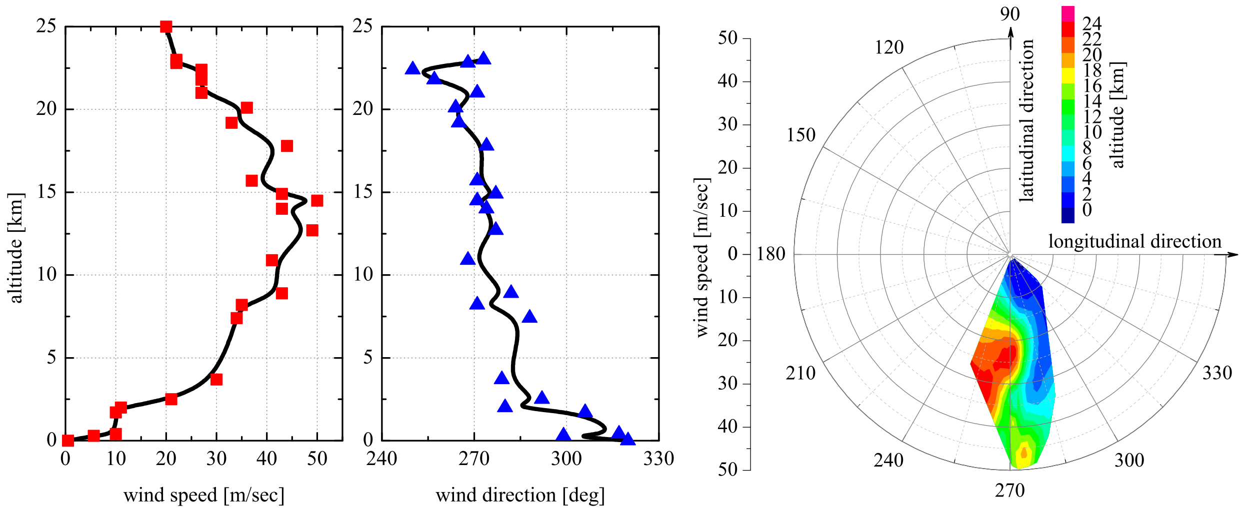
in which $C_d^{(\mathrm{tether})}$ is a drag coefficient of the tether cable. A tether rope can be assimilated as a two-dimensional cylinder since a cross section of this tether rope is regarded as a circle with 50 [mm] diameter. $\rho_{\mathrm{air}}(z)$ [kg/m^3] is air density, which is a function of an altitude z. $w(z)$ [m/sec] is a wind speed, which is also an function of an altitude z. $S_{\mathrm{ref}}^{(\mathrm{tether})}$ [m^2] denotes a reference area of the tether cable.

An initial condition is chosen at the connecting point of the tether cable and the vehicle, which is located at the top end of the tether cable, thereby, analysis can be made in terms of Eq. (6) as differential equations of T and θ. When a tension and an elevation angle at the top end of the tether cable are respectively defined as T_0 and θ_0, the initial condition can be geometrically determined with the following equations.

$$T_0 = \sqrt{(L+B)^2 + D^2}, \tag{8}$$

$$\tan\theta_0 = \frac{L+B}{D}, \tag{9}$$

where, L, B and D respectively indicate an aerodynamic lift, buoyancy, and a drag of the LTA hull.



(a)

(b)

Figure 2. Wind data for the present analysis. (a) The wind data regarding speed and direction as the input for analysis under the condition of windstorm from the meteorological agency in Japan. The plots are the exact data and the black curve is proximate B-spline. (b) Visualization of the data shown in (a) on a two-dimensional plane. The length describes wind speed. As direction corresponds to that of the map, 90 [deg] shows the north direction. Colors denote altitudes.

B. Computational Conditions

Computational conditions regarding the tether cable are summarized in this Section. $C_d^{(\mathrm{tether})}$, which is roughly estimated to allow reasonable tolerance, is set to be 1.5 as a drag coefficient against air flows around a three-dimensional cylinder under the circumstances of Reynolds number Re from 10^5 to 10^7. Interpolated wind data have generated from data supplied by Japanese meteorological agency are employed for $w(z)$. Since a diameter of 50 [mm] for the tether cable is assumed, $S_{\mathrm{ref}}^{(\mathrm{tether})}$ becomes 50 [m^2]. The tether rope specific weight is also assumed as 3×10^3 [kg/km].

Meanwhile, computational conditions regarding the LTA vehicle are also summarized here. A drag coefficient of the vehicle is assumed to be 0.06. Wind speed around the vehicle hull is chosen as 50 [m/sec], which is the maximal speed among the available wind data presented in Fig. 2. The conceived LTA vehicle has the total buoyancy of 160 [ton]. In the studies here it is assumed to utilize hydrogen gas for a buoyant gas to inflate the LTA. Although hydrogen has a high advantage in density different from the air, there exist thoughts that hydrogen should be circumvented as it can be easily ignited. However, reconsideration can also be made, in which protection measures can be taken against this easily ignited nature by choosing appropriate materials to fabricate a gas holding hull. Let us assume to adopt hydrogen here, then, the following equation can yield buoyancy B from a displacement volume of the gas holding envelop V and from difference between air density ρ_{air} and hydrogen gas density $\rho_{\mathrm{H_2}}$.

$$B = V(\rho_{\mathrm{air}}(z) - \rho_{\mathrm{H_2}}(z)). \tag{10}$$

Since an aerodynamic reference area of the vehicle is defined as $V^{2/3}$, this reference area can be determined by Eq.(10). If B is 160 [ton], then V becomes roughly 1.4×10^6 [m^3]. Total drag of the vehicle hull usually becomes minimal when a ratio of the major axis of the spheroidal hull versus its minor axis is chosen as approximately 3.9[10]. Thereupon, the minor axis will be approximately 40 [m].

C. Captive LTA System Behavior

Computations were carried out from the ground level to an altitude of 20 [km] since the captive vehicle is expected to be floated in the lower stratosphere. Figure 3 shows the system behaviors in two cases that L is zero and L is equal to B. This figure shows that the order of advection distance of the vehicle is 10^0 [km] from a mooring point on the ground even if the vehicle does yield no lift under stormy conditions. Pay attention to a point that this order of the advection distance depends on a small value of C_D, which is 0.06

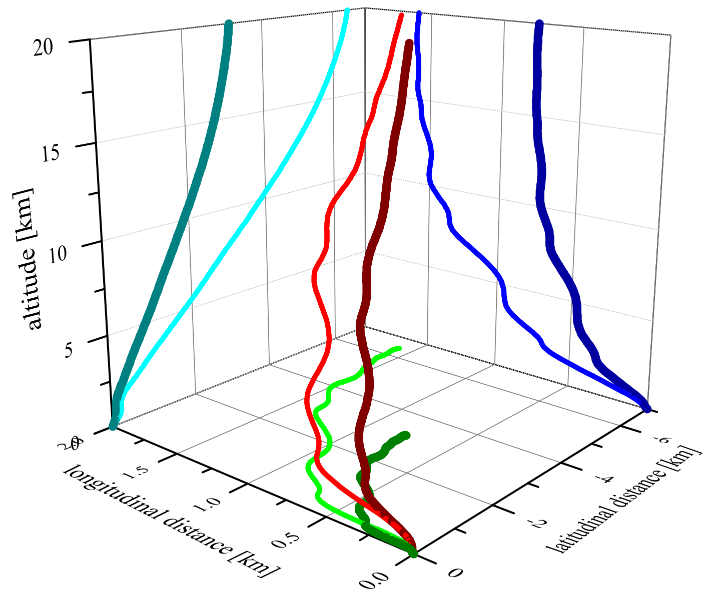


Figure 3. Computational results of the system behavior for an axisymmetric hull and a hybrid hull. Primary colors describe results for axisymmetric hull shape ($L = 0$), obscure colors describe results for hybrid hull structure ($L = B$). Red shows the three-dimensional behavior of tether, green shows the result that the three-dimensional behavior of tether is projected onto x-y plane, blue shows the result projected onto x-z plane, and cyan shows the result projected onto y-z plane, respectively The origin is set to be a connecting point on the ground.

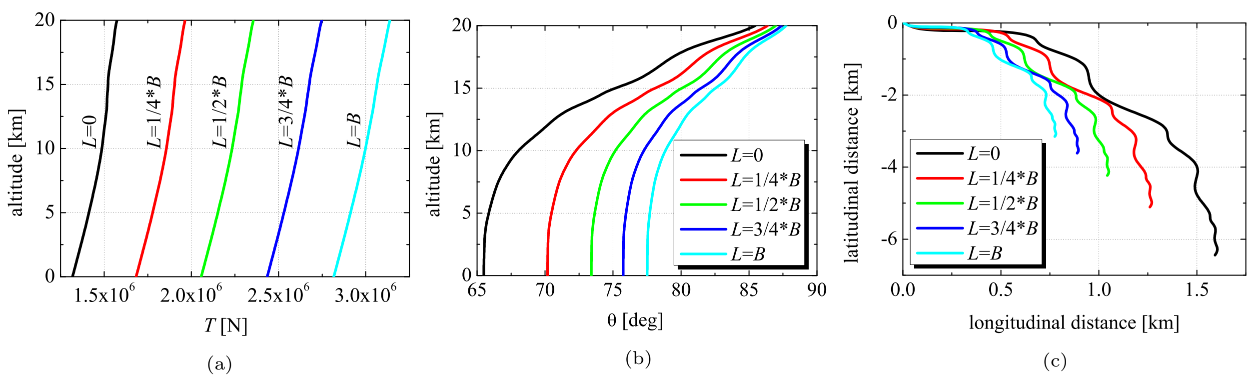


Figure 4. Effects by L-variations on the tether cable. (a) Tether cable tension T versus altitudes. (b) Tether cable elevation angle θ versus altitudes. (c) Tether cable silhouettes projected onto the ground, namely x-y plane; ground mooring point as their origin.

for the vehicle. Moreover, Figure 3 also demonstrates that dynamic lift developed by hybrid LTA vehicle reduces advection distance. The system behaviors vary according to wind speeds and their directions.

Figure 4 shows effects of L variation onto the tether line. The corresponding outcomes of T are shown in Fig. 4(a). L variation effects seem to be linear on the tether tension. However, there is no linear correlation of the initial value of tension T_0 because there is nonlinearity between the lift fluctuation ΔL and the tension fluctuation ΔT described by Eq. (8). As a result, the tether tension has non-linear behaviors for L. Moreover, the minimal tension is loaded on the mooring connection point of the tether rope with the ground. Namely, the higher the altitude is, the greater becomes the cable tension. The results indicate that the connecting point of the vehicle with the tether rope end has the most severe loading point compared with the rest of the cable. Methods of making a knot connecting the vehicle hull and the tether cable end should be paid special attentions.

On the other hand, the variation of θ can be observed in Fig. 4(b). This data show non-linear behaviors of θ. There is no linear tendency of θ_0 because there is no linearity between the fluctuation of lift ΔL and the fluctuation of elevation angle $\Delta\theta$ described by Eq. (9). As a consequence, θ has non-linear behavior with respect to L. Therefore, advection distance becomes non-linear as is shown in Fig. 4(c) which is projected onto the x-y plane. Moreover, as is shown in this figure the more L increases, the shorter becomes the advection distance of the vehicle. That is, since the effect of shortening advection distance is remarkable, from a point of effective L generation, an ordinary axisymmetric hull seems not much advantageous because of that type of hull shape yields less lift. In this sense, hybrid type LTA vehicles look very hopeful for a captive lower-stratospheric LTA platform.

III. Captive High-Altitude Platform System

Creation of a stratospheric station-keeping platform is an attractive concept for wide area of applications, for example, communication, meteorological observation, remote sensing and a high altitude launch pad for space vehicles. Preferable altitude depends on missions, but station keeping capability together with vehicle attitude stability including the tether line would be the highest priority to be taken into account for a multiple use platform. Regardless of application areas, a multipurpose use platform must be provided with transportation means to exchange different payload and to meet variety of missions, and this requires unique shuttle-type optional transport equipment.

Tether cable length limits maximum altitude of the platform. Presently available high specific strength materials enable us to design a tethered platform floating over 20 [km] high altitude. Deflections of the catenary tether cable by winds have been analytically examined1). And their results are presented in Fig. 3. Horizontal deviation of flight position from a ground-based mooring station primarily depends on a ratio between vertical and horizontal forces imposed upon the vehicle. The vertical forces consist of buoyancy and aerodynamic lift to the vehicle hull. The horizontal force is aerodynamic drag. Propulsive force can contribute largely to the horizontal force, but the authors have other ideas and regard the propulsion as optional in this paper since propulsive devise consumes considerable amount of energy. In order to enhance vertical force in high windy circumstances, hybrid LTA designs seem to be attractive. But effects of aerodynamic lift should be carefully examined in detail since the lift increases tether cable tension. After all, a tether rope is always pulled upward even in a deployment phase. Floating altitude much higher than 20 [km] would be presumably feasible by series connection of LTA vehicles seen as series connected kites which are often demonstrated in the amusement events.

Presently available impermeable films enable to keep an LTA platform for a long duration mission in the sky, for an example 10 years or so. However, unexpected gas leakages could happen in actual circumstances. In these cases, buoyant gas must be supplied. It could be effective to trickle buoyant gas to the vehicle through a thin flat tube along the tether cable.

Unmanned operations will be essential for practical system design. A mobile robot on the hull surface will be necessary besides end effectors located at some specific equipment. For these devices, teleoperation systems must be provided beforehand. Needless to say, these systems depend essentially on telecommunication.

A. Vehicle Stability

The static pitching stability of the vehicle is examined in terms of moments around the center of gravity generated by aerodynamic forces, buoyancy and tether tension as indicated in Fig. 5. In this case, the connecting point between the hull and tether is assumed to be single. Equation (8) and the following equations are geometrically derived.

$$\begin{aligned} &T_0 \cos\theta_0 = D, \\ &\delta_T = \delta_{\mathrm{P}_c} \sin\{\theta_0 - (\alpha+\beta)\}. \end{aligned} \tag{11}$$

The vehicle pitching dynamics in a situation shown in Fig. 5 are described by the following equation.

$$I\frac{\mathrm{d}^2\alpha}{\mathrm{d}t^2} = -\frac{1}{2}\rho v^2 S_{\mathrm{ref}} C_{m_\alpha}\alpha + T_0\delta_T + B\delta_B. \tag{12}$$

I, S_{ref}, and C_{m_α} are respectively moment of inertia, hull reference area, and pitching moment coefficient. As δ_T becomes less, it seems to keep static stability. When the vehicle is in a stall condition, α diverges into unmanageable state. In most of hull designs, the center of buoyancy and the center of gravity are located close to each other and are almost vertically collinear. But a tensile point of a tether rope will be

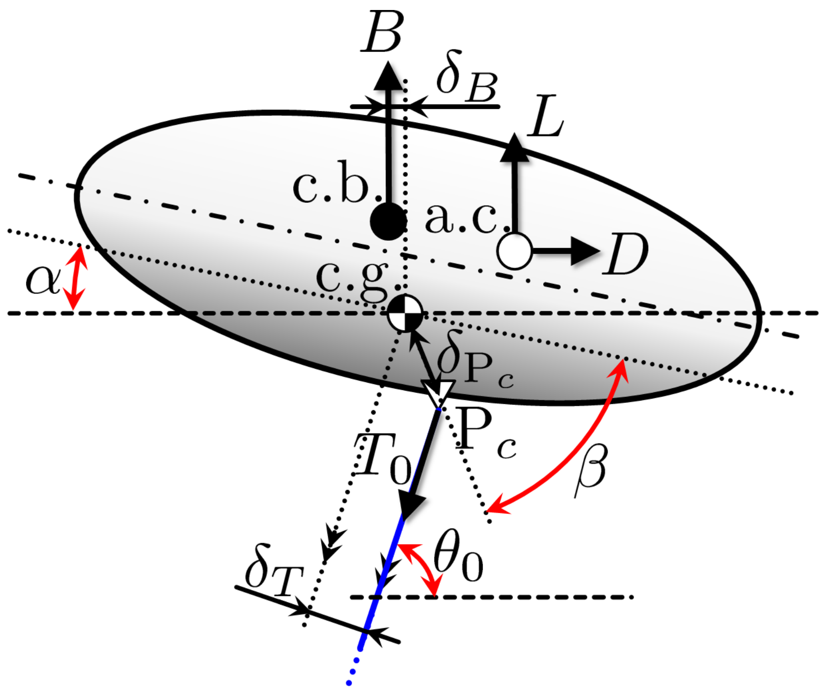


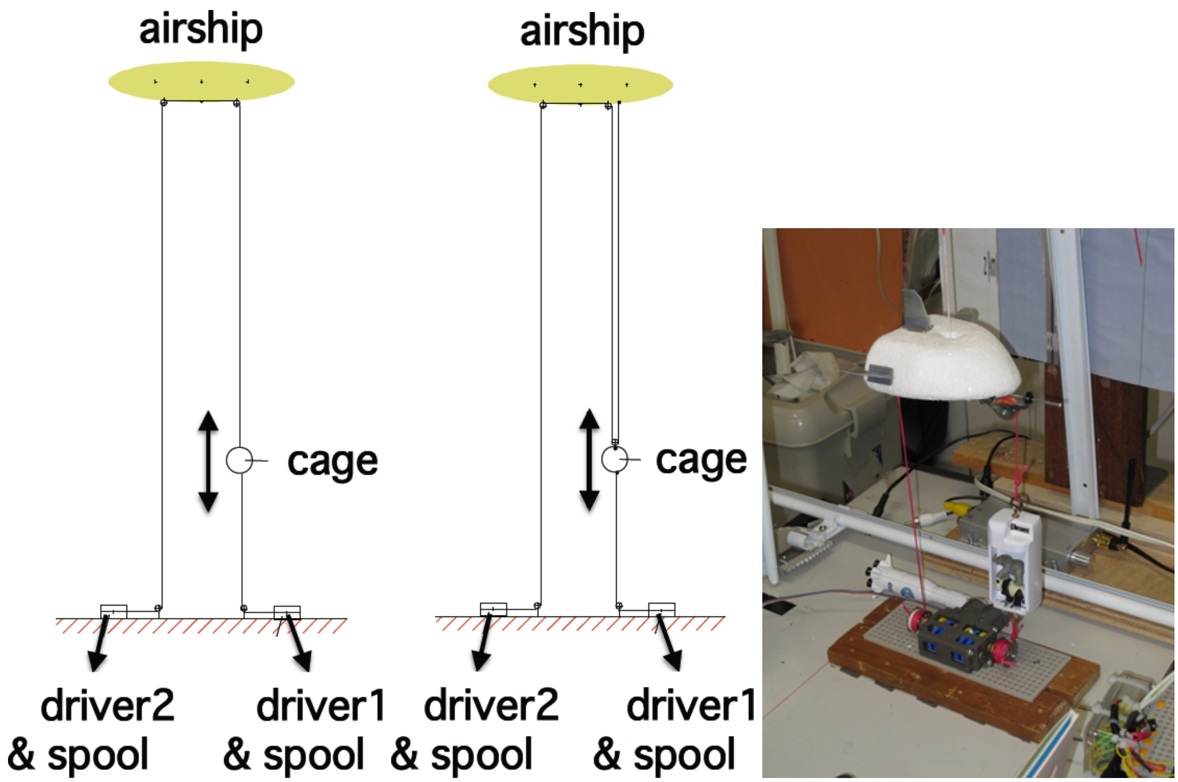
Figure 5. Diagram for analysis on pitching stability; aerodynamic center "a.c.", center of buoyancy "b.c.", center of gravity "c.g.", connecting point of hull to tether rope top end "P_c". Blue colored line shows tether cable.

considerably far from them due to a large diameter of the hull. It will affect a substantial magnitude of moment around the center of gravity. For this reason, the aerodynamic center should be properly positioned rearward. If necessary, a tensile incurred position could be made a control parameter to adjust an angle of attack α. Hybrid LTA designs must be taken into account of enough stability margins, as well as roll stability performances. Figure 6 shows a miniature-scale model of hybrid LTA vehicle floated at a 200 [m] altitude above the ground level in order to study such stability problems.

B. Elevator

In order to climb up to the platform, self-powered shuttles called "climbers" have little advantage compared to elevators towed by a cable from the ground facilities. The primary advantage of such elevators is free

Figure 6. A small-scale hybrid LTA vehicle model.



(a) (b) (c)

Figure 7. Two types of elevator systems. (c) is a trial-made model of type (a).

from power supply problems. Required ascent power P for a climber or an elevator is estimated by

$$P = Mgv + \frac{1}{2t}Mv^2, \tag{13}$$

where, M, v, and t respectively denote mass, velocity, and time for acceleration. When M of 1 [kg], v of 10 [m/sec], and t of 2 [sec] are assumed, this equation indicates that P needs 125 [W]. Also, when the conveying mass amounts to 500 [kg], required power becomes 62.5 [kW], which corresponds to a power level of an ordinary engine's output equipped to a civil use passenger automobile. Two kinds of elevator systems are indicated in Fig. 7. In the simplest system shown in Fig. 7(a), carrying load capacity is less than a half of the total lifting force $(B + L)$. A half of lifting force is allocated to the tether cable tension for holding the vehicle in the air. To increase transportation capacity, force conversion mechanisms shown in Fig. 7(b) would be effective. In this example, usable lifting force for an elevator amounts to 2/3 of the platform's total lift. For an indoor miniature model test, equivalent buoyancy was given by a constant loading spring. The essential point of this idea shown in Fig. 7 is that more than two points are connected to tether cables under the hull surface. In this way, pitching angle of the platform can be controlled by using these tether cables.

IV. Avionics

Hybrid LTA vehicles also require avionics in order to obtain flight data during their operations. Furthermore, these avionics can be utilized as a guide rope for an elevator toward the platform. It will be also useful, if the acquired data could be transmitted to the ground station in real time.

Figure 8 shows conceivable block diagrams of such avionics system. Developed avionic equipment is shown in Fig. 9. If only a global positioning system (GPS) is utilized for avionics, positioning accuracy for altitudes is not much good compared with that for horizontal positioning. Therefore, an atmospheric pressure sensor is necessary for corrections of GPS altitude data. ZigBee unit is adopted for communication between avionics

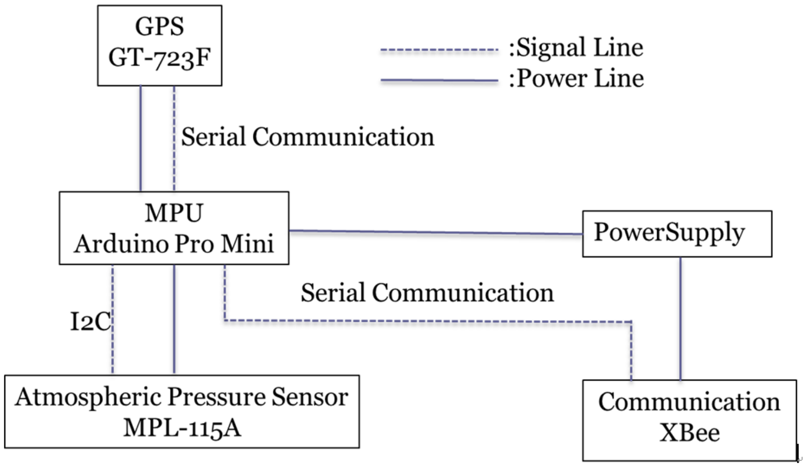


Figure 8. Block diagram of proposed avionics system.

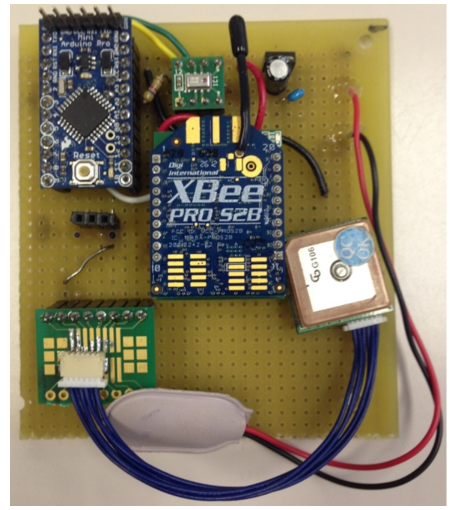


Figure 9. Developed avionics equipment.

and a ground station. In the near future, if an experimental prototype vehicle is developed, a communication system with directionally controlled antennas is necessary for telecommunications. The following sections give summaries for two telecommunication candidates investigated this time for telecommunication.

A. Laser Beam Communication

Development of a radio communication system is necessary in order to practically control a vehicle in the air. A laser beam wireless communication system is appropriate for LTA platforms. Because the laser system has high-speed communication performances and no formal specific license is required in order to operate the system. Our laser communication test was successfully carried out that was estimated to realized 100 [Mbps] transmission speed at a distance of roughly 15 [km] in urban areas on the ground level. Figure 10 is a photograph of the experiment. The photo was taken at a receiving point on the laser beam emitted from the source. According to our technical paper survey, it can be considered as the longest distance record in the world as laser beam communication test between ground-based stations. This communication method has various advantages even in cloudy conditions. In the next step, the most important challenge is development of a directional control system to transmit and receive laser beam for communication. This control system is considered as an automated beam tracking system with high precision mirror tilt mechanisms. The conceived block diagram is show in Fig. 11.

Figure 10. Laser beam at receiving point.

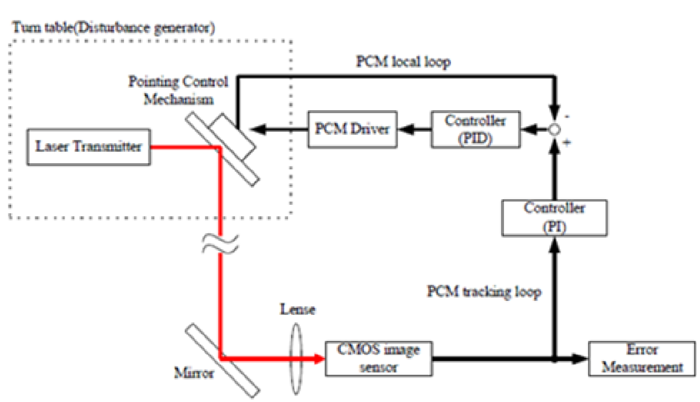


Figure 11. Block diagram for on-board system.

B. Utilization of D-STAR

One of simple and practically available radio wireless communication methods is Digital Smart Technologies for Amateur Radio (D-STAR). D-STAR is a standard technology developed by the Japan Amateur Radio League (JARL). This technology has been widespread in the world. D-STAR is for direct communication or communication via a repeater, and is a novel generation amateur radio technology that achieves a relay between the repeater on internetwork, etc. In accordance with the law, D-STAR cannot be used for pecuniary purposes. Individuals and organizations are allowed to utilize it when they are only interested in wireless communication technology itself. However, D-STAR on board of high altitude LTA vehicles is possible to achieve highly effective communications in emergent occasions, such as disastrous earthquakes. Nowadays novel air-born type D-STAR repeater system requires small size, light weight and power saving device. It is as well necessary to be officially supervised by Ministry Internal Affairs and Communications with the help of JARL in order to achieve the above mentioned application.

V. Concluding Remarks

The experimental results of flight tests, tether system operation tests, and wireless communication tests have been presented and their analysis summaries are also given in order to materialize a stratospheric platform as a hybrid lighter-than-air vehicle with its tether system.

Expected feasibility studies in the next stage will include effective technology to effectively operate the conceived elevator. When a tether cable is utilized for conveying electric power, weight of the tether cable becomes heavier. On the other hand, if wireless electric power transmission is adopted, the vehicle itself becomes heavier due to required additional devices such as antenna and accompanying instruments. Compromise solution shall be investigated in order to realize an efficient high-altitude captive lighter-than-air platform system.

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