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Cable-Supported Sliding Payload Deployment from a Circling Fixed-Wing Aircraft

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I. Introduction

IT is often desirable to deploy or deliver payloads quickly to remote locations during military conflict or peacetime survival support. One option is to use helicopters, which can hover stationary over the desired drop location, or land in regions with sufficient open space. There is no question that such techniques are preferred, particularly for rescue operations. However, the ability to perform such missions is limited by the speed and range available to helicopters. On the other hand, aircraft can fly greater distances in shorter time but the majority of remote locations are not equipped with sufficient conditions to allow an aircraft to land. This is most evident for operations over the ocean. To overcome this, a variety of airdrop techniques have been used to deliver equipment and supplies. See Ducote and Speelman [1] for an early survey of several techniques used by the U.S. Air Force. Some recent issues related to the effectiveness of airdrop techniques and possibilities for increasing the precision of high altitude airdrops were discussed by Bagdonovich et al. [2]. Conventional airdrop techniques use ballistic parachutes to deliver payloads, and require accurate preplanning and in-flight updates to accommodate for wind variations and other factors influencing the accuracy of the drops. Another possibility that was pioneered in the 1940s by a missionary pilot, Nate Saint [3], and subsequently studied numerically [4–8] is to use a cable deployed from an aircraft. It has been demonstrated that a cable with a sufficient drag-to-weight ratio of the cable end body can be made nearly stationary in inertial space by having the aircraft fly tight, constant diameter circles [8]. In fact, this technique has been used to deliver and retrieve small items by using a bucket or canvas bag at the cable tip [3]. However, one major drawback of using the cable tip to deliver payloads is that the stability of the stationary motion depends directly on the weight of the attachment. In Williams and Trivailo [8] it was demonstrated that increasing the tip mass increases the steady-state circular radius achieved by the cable tip. Furthermore, cable lengths on the order of 3 km are required to achieve good stability, and so deploying/retrieving the cable to deliver multiple payloads is a serious shortcoming of the method. In this Note, a technique is proposed that can solve some of these difficulties. Figure 1 shows an illustration of the basic system. An aircraft is required to fly constant diameter circles with a towline attached. The end of the cable approaches the center of the circle due to the natural dynamics of the system. When the cable tip touches the ground it is preferably anchored, or if the operating surface is water, the end is placed into the water to provide high damping. The payload is then “hooked” onto the cable and slid to the ground/water. The technique could potentially also be used to retrieve payloads, provided that a powered mechanism can be designed to climb the cable.

Virtually all past studies of the dynamics of circularly towed cable systems have dealt with the stability of the cable motion, whereas comparatively few have studied the transient dynamics. Clifton et al. [7] used an inextensible, continuous model of the cable to study the dynamics of such a system. More recently, Williams and Trivailo [8] sought practical towing solutions for different types of aircraft and optimized the system parameters subject to aircraft performance constraints using a lumped mass cable model. Only unique, stable solutions were reported. This was followed by studies of the transition dynamics to and from circular flight using a lumped parameter dynamical model [9]. The dynamics of cables with an attached sliding mass has been the subject of previous research. In particular, the behavior of a cable with a rocket-propelled trolley has been studied because of the use of such systems for impact testing of aircraft components at Sandia Laboratories, Albuquerque [10]. Rodeman et al. [11] noted that the cable failed during a test as the moving mass accelerated beyond the wave speed of the cable and derived a numerical solution for an idealized infinite string with a uniformly accelerating mass. Tadjbakhsh and Wang [12] considered

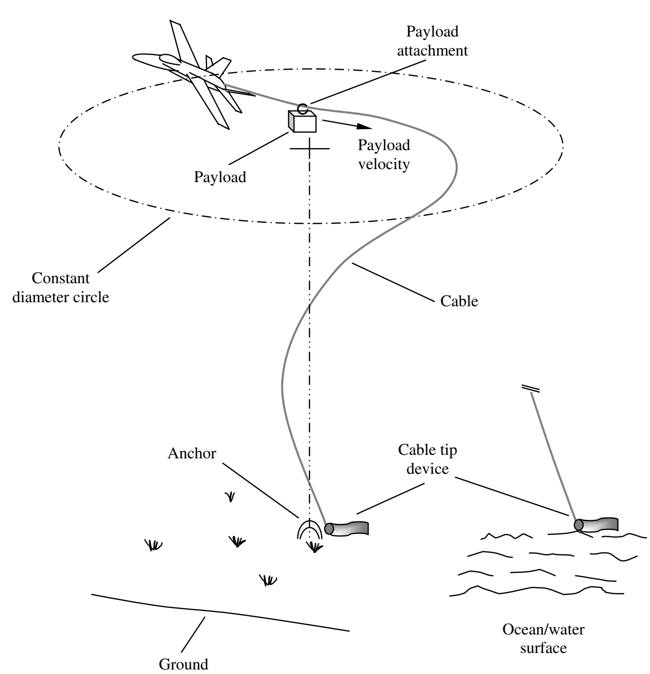

Fig. 1 Basic system arrangement for sliding payload delivery.

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the dynamics of an inclined cable with an accelerating mass by superimposing small deformations on the static catenary shape. A finite element formulation with a "sliding" element was presented by Zhou et al. [13] to capture the effect of a cable sliding over a point but frictional effects were ignored. Williams [14] recently developed a general lumped mass model for a cable incorporating the effect of a sliding mass element with arbitrary applied forces.

In this Note, a lumped mass model is used to study the dynamics of the proposed delivery technique and to establish how some of the key system parameters affect the overall performance.

II. Simulation Model Description

The aircraft-towed cable system is modeled using the lumped mass approach. This is a very common method for modeling complex cable dynamics and has been validated experimentally. The lumped mass approach is similar to a finite element approach, except that the inertia properties of the cable elements are lumped to individual points. Each point mass is connected sequentially by a viscoelastic spring and is acted on by aerodynamic drag, gravitational loads, and frictional effects due to the sliding payload. For a circularly towed system, a rotating coordinate system is used so that the cable relative equilibria appear stationary in the rotating frame. The aerodynamic forces are calculated based on nonlinear normal and tangential loading functions presented by Buckham et al. [15]. The cable end mass is assumed spherical and generates only drag. The equations of motion for the cable system are similar to that described in Williams and Trivailo [8] and Buckham et al. [15] and are omitted here. The major difference in the model arises from the introduction of a sliding mass element. Blanksby and Trivailo [16] presented an approach for modifying the motion of a tether modeled via lumped masses due to contact with another structure. However, they did not consider the motion of a mass sliding along the cable and the coupling between the two. Williams [14] modeled the presence of the sliding mass within the lumped parameter framework by considering the slider as a free mass subject to normal and frictional forces from the cable, drag, gravity, and propulsive or other applied forces. In this approach, the cable forces are computed via the constitutive law of the material based on the geometric deformation caused by the slider. The frictional and elastic forces due to the sliding element are applied to the lumped masses in the standard lumped parameter framework. The model of the sliding cable element has been validated against numerical results generated in Tadjbakhsh and Wang [12], and these are presented in Williams [14].

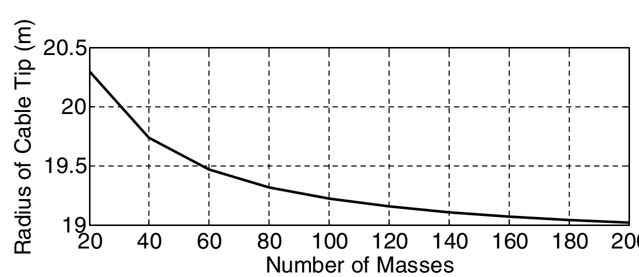
In this paper, no explicit modeling of the attachment of the payload to the cable is undertaken. However, the design of the attachment has important consequences for whether active braking of the payload can be undertaken with a friction brake. The payload could be attached via a pulleylike mechanism, which would allow active braking, whereas a hook/ring attachment would only allow some form of aerodynamic braking of the payload via a parachute. Another important design consideration is whether the attachment mechanism should be completely detachable from the cable, so that when the payload approaches the cable tip it automatically detaches itself, or whether only the payload is detached. The latter option would allow each mechanism to be reused after retrieving the cable. Finally, the focus of this Note is on payload deployment, but it should be noted that it may be possible to retrieve payloads using a motorized climber through a similar technique.

It is known that the equilibrium configuration of the cable is strongly dependent on the weight of the cable tip mass [8]. Thus, if a reasonably large payload is slid along the cable, it is likely to cause an apparent instability in the cable and an enlargement of the radius of the orbit of the cable tip. This in turn affects the accuracy of the delivery, and lengthens the time between subsequent deliveries due to the relatively long time constants involved in the fundamental vibration modes [8]. One possible way of reducing or eliminating this effect is to "anchor" the cable tip. This could be achieved, for example, with a ground support crew or a mechanism capable of injecting itself into the ground. In the latter case, the mechanism would need to be equipped with a release mechanism to allow the cable to be retrieved. Simulations of the system suggest that anchoring is the preferable option and hence the simulations performed in this work are for the anchored case.

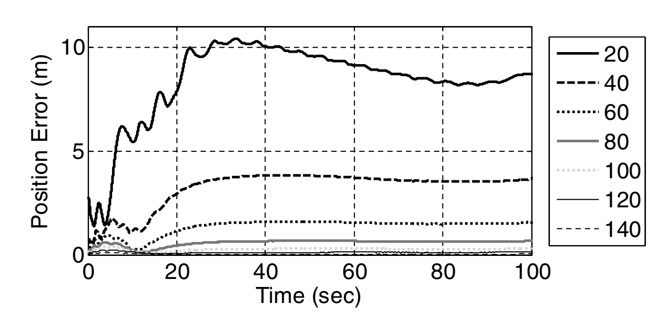
III. Numerical Simulation Studies

It has been found through numerical simulation studies that certain cable configurations provide better stability during sliding payload deployment. Configurations with higher nominal tension, achieved by using a larger diameter cable and/or higher material density, tend to provide much better stability for the payload. This can be easily understood by recognizing that the deflection of the cable caused by a moving load is directly related to the cable pretension. Thus, it is necessary to choose the cable parameters carefully to obtain a good combination of small tip radius and cable pretension. The maneuver design for particular configurations and cable deployment has been addressed in Williams and Trivailo [8,9] and will not be elaborated on here.

The main parameters that are used throughout this paper are as follows: Cable mass density 3000 $\mathrm{kg/m^3}$, Young's modulus 37.5 GPa, cable tip mass 5 kg, cable length 3 km, aircraft speed 60 m/s, aircraft orbit radius 300 m, friction coefficient 0.08, and cable drag coefficient 1.2. The nominal cable configuration in this paper uses a cable diameter of 8 mm. The air density is assumed to follow the international standard atmosphere. Using these parameters, the steady-state orbit radius of the end mass is on the order of 19 m, or 6.33% of the aircraft orbit radius. Thus, it would be possible to deliver small payloads to within 20 m of a target with the cable tip free. Figure 2a shows the convergence of the steady-state orbit radius of the cable tip with the number of cable elements. This suggests that even moderate numbers of elements, for example 20, can produce results accurate to about 1 m. Figure 2b shows the effect of the cable discretization on the convergence of the sliding payload dynamics. Note that 160 elements were used to compare the error. Larger numbers of elements become prohibitively slow for computational purposes. Figure 2b illustrates that even 20 elements predicts the motion of the payload to within 10 m accuracy. It should be noted that an additional small error is incurred because the payload position is not precisely the same at the initial time. However, it can be seen that 100 elements produces quite accurate results and this is used in the remainder of this Note.



a)



b)

Fig. 2 Effect of cable discretization on solution: a) Steady-state radius of cable tip (free), b) Total relative position error of 100 kg sliding payload with respect of 160 element solution for various numbers of elements.

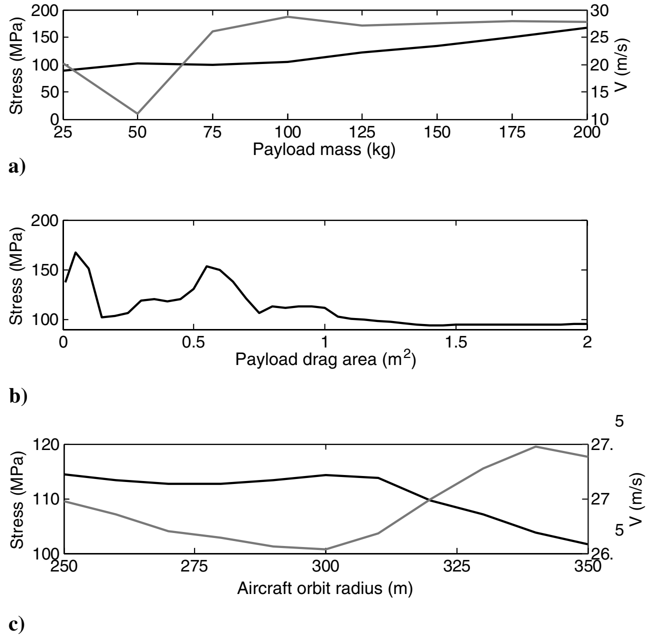


Fig. 3 Numerical simulation results for sliding payload deployment: a) Effect of payload mass on maximum cable stress and final velocity, b) Effect of payload drag area on maximum cable stress for a 75 kg payload, c) Effect of aircraft orbit radius on maximum cable stress and final velocity for a 100 kg payload.

Some basic parametric studies of the effects of different system parameters were performed using the model and the results are summarized in Fig. 3. Figure 3a shows the effect of payload mass on the maximum cable stress and velocity of the payload at the ground. It is clear that increasing the payload mass increases the maximum cable stress. These calculations were performed with aerodynamic drag (passive braking) applied to the payload using a quadratic drag model with the $(\text{drag coefficient} \times \text{drag area}) = 0.1768\sqrt{m_s}\ \text{m}^2$, where m_s is the payload mass. It is necessary to use some kind of braking to slow the payload for two reasons: To reduce the velocity of the payload at the ground, and to prevent the payload from tripping the cable dynamic instability. As discussed in Rodeman et al. [11], the instability of the cable is generally dependent on the speed on the moving load. Hence, it is necessary to keep the speed of the payload low. Numerical simulations show that without any passive braking the cable instability is tripped. Figure 3b shows the effect of the drag area of the payload (75 kg) on the maximum cable stress during the deployment. For drag areas less than approximately $1\ \text{m}^2$, the cable instability is significant. However, drag areas greater than $1\ \text{m}^2$ tend to reduce the speed of the payload to levels acceptable for this particular cable configuration and the cable instability is markedly reduced. It would also be necessary to use additional braking when the payload approaches the ground to reduce the impact velocities shown in Fig. 3a, which are on the order of $27\ \text{m/s}$. Optimization and design of an appropriate braking system is therefore an important aspect that must be considered for the realization of such a payload delivery system. Figure 3c shows the effect of varying the aircraft orbit radius on the maximum cable stress and velocity of the payload at the ground for a 100 kg payload. The aircraft orbit radius does not alter the velocity of the payload at the ground to any substantial degree, but a larger aircraft orbit appears to reduce the cable stress for this particular set of system parameters for radii larger than approximately 310 m.

IV. Conclusions

A novel concept for the remote delivery of payloads from a fixed-wing aircraft has been presented. The concept uses a taut cable deployed from a circling aircraft as a support structure for sliding payloads from high altitude to the ground. Anchoring the cable tip guarantees accurate positioning of the cable tip on the ground. Simulations of the cable dynamics suggest that it is necessary to use some form of braking to slow the descent of the payload. If the payload speed is too excessive, then the cable dynamics can become unstable and the peak tension can reach high levels. Further work is necessary to investigate many of the design features that could improve the performance of such a system, such as optimization of the aircraft orbit and application of a controlled braking profile.

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