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MOBILE LAUNCHING TREBUCHET FOR UAVS

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Abstract

A trebuchet was a kind of siege engine in the middle age that launched the projectiles well above the ground. We've found a trebuchet-like solution to launch UAVs in safe altitude. The feasibility studies were based on a multibody model described with a non-linear differential equation system. Studies showed the energy demand of the launch can be stored in the potential energy of the transport vehicle of the UAS. The theory was verified by a series of launch tests. Finally a simple, maintenance free and cost effective prototype was developed for UAV launch with the unique high release feature. The patent of the solution is pending.

1 Introduction

A trebuchet was a kind of siege engine in the middle age that was characterized by an arm-and-sling mechanism and a heavy counterweight that stored the required energy for launching a projectile in its potential energy ([1]).

Fig. 1 Trebuchet in the middle age [2]

The increased release height of this solution appeared to be useful today for fixed wing UAVs, because the widely used catapults ([3],[4],[5]), bungee starts and similar solutions feature low release height and low flight path angle during climb, that require clean, obstacle free area. However a trebuchet releases the projectile in 5-10 meters i.e. above bushes, small trees, camp accessories, small buildings etc. We started an investigation whether this advantage can be utilized for launching a fixed wing UAV.

2 Arm-and-sling mechanism

The increased release height is the result of the arm-and-sling mechanism originally developed for launching heavy projectiles. As a first step we investigated if a trebuchet can be used with a relative light UAV with low speed.

2.1 Simulation

For the first, approximate investigations we simplified the counterweight and the UAV to point masses and set up a system formed by two bodies. The first body consisted the sling together with the UAV, while the second one consisted the arm together with the counterweight. (Fig. 2)

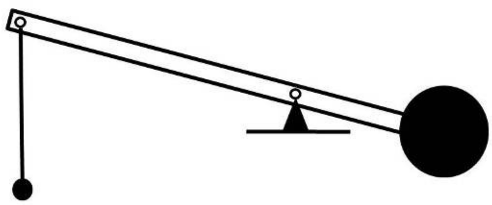


Fig. 2 Simplified model of an arm-and-sling mechanism

The dynamics of the model was calculated by a differential equation system implemented in MATLAB M-code. The integration was solved by a Runga-Kutta method of 4-5th order.

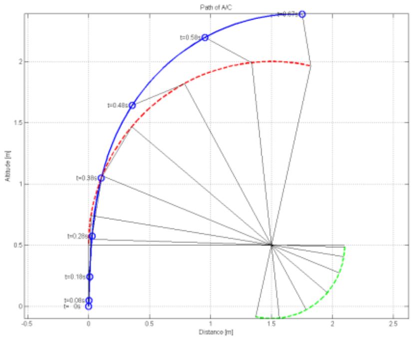


Fig. 3 Visualisation of the simplified trebuchet simulation

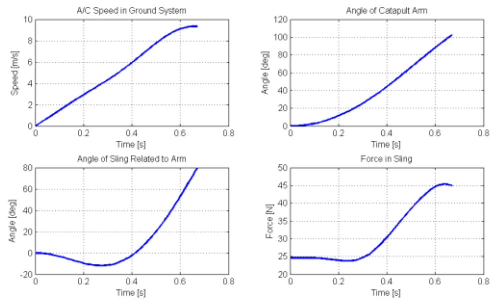


Fig. 4 Time function of parameters during launch

Fig. 3 demonstrates a launch, while Fig. 4 shows the time function of the parameters during the event. The arm starts in a horizontal position then the counterweight rotates it about the pivot axis. In the first phase of the launch the sling keeps his approximately perpendicular position to the arm, but at t≈0.4s the UAV and the sling starts to rise. At the end of the simulation the sling is approximately parallel to the arm and UAV reaches its highest point. The angle between the arm and the sling increases monotonically providing a very simple solution for releasing the UAV. The speed of the UAV increases with approximate constant acceleration, while the force in the sling is approximately constant in the first phase and increasing in the second phase.

We investigated the effect of different parameters in the simulation like:

- weight of counterweight
- length of arm
- position of pivot
- length of sling
- weight of UAV

and set up a table of parameter sets enabling successful launches.

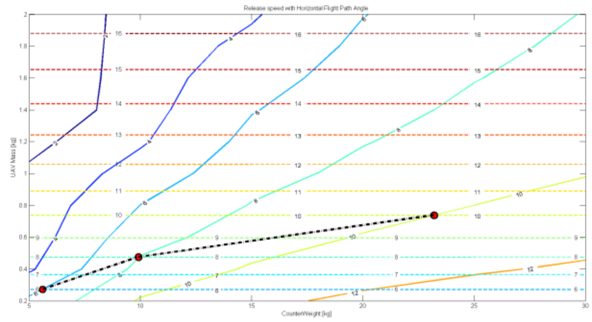


Fig. 5 Speed available and speed required

Fig. 5 shows a kind of speed available and speed required plot for a given UAV (Wing surface S=0.1m^2, max. lift coeff. C_{Lmax}=1.2, altitude h=0m MSL) in case of different counterweights (horizontal axis) and different takeoff weights (vertical axis) combinations. Continuous lines representing the speed available during launch because they are connecting points representing 'counterweight – UAV' weight combinations resulting the same launch speed (isovelocity curves) and labeled with the amount of speed measured in [m/s]. The dotted lines representing the speed required, namely the stall speed [m/s] of the UAV having the weight equal to the value, which can be read at the vertical axis of the diagram where the dotted lines crosses it. Dotted lines are horizontal because they aren't a function of the counterweight. Red dots were placed at several points, where continuous and dotted lines with the same label are crossing (5 m/s, 8 m/s, 10 m/s respectively). At these points the speed provided by the device is equal with the stall speed of the UAV. One can read that the above mentioned UAV in case of a takeoff weight of 0.5kg, can be launched by a counterweight of 10 kg. (Middle red dot.) If the takeoff weight will be increased by 50% to 0.75kg, a successful start requires a counterweight of 23.5kg. (Third red dot.)

2.2 Validation

In order to validate the results of the simulation we built a small scale trebuchet and a set of counterweights. We used a freeflight airplane made of durable and easy to repair EPP.

Fig. 6 Small scale trebuchet

The release of the UAV near the top of the launch path is ensured by the separation of a metallic ring at the end of the sling from the release pin at the end of the trebuchet arm. The separation happens automatically at a given angle between the sling and arm. The angle can be adjusted by the direction of the release pin. The solution is originated in the middle age and fortunately must be modified only slightly to the application of UAVs, while its simplicity and reliability remained.

3 Mobile trebuchet

3.1 Configuration

After the promising preliminary results we've collected the requirements for a reasonable, full scale device capable of launching a UAV in the class of 10kg. The most important requirements were the mobility: the device had to be easy to transport and easy to install in order to make it competitive to the existing solutions. These requirements could be met only if the counterweight is the vehicle (car, rover, van) itself, that is used to transport the crew and all of the parts of the unmanned system. Additionally the heavy supporting structure of the original trebuchet had to be minimized in order to make it lightweight and simple enough for a single man crew. The following patent pending solution (Fig. 7) utilizes the transport vehicle as counterweight and even as the most of the supporting structure, too. The operation of the mechanism is similar to the floating arm trebuchet ([6]) but instead of roller-and-track constraints we applied simple, lightweight and easy to maintain bearings and linkages.

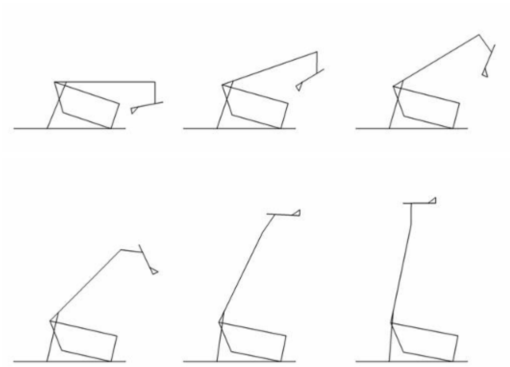


Fig. 7 Kinematics of the mobile trebuchet

This solution seems unorthodox, but in addition to the high release feature it is very cost effective, too. No special high power energy storage device such pneumatics, rubber bands, electric launch motor, etc. is needed, resulting low material, production and maintenance costs. The simple release solution of the UAV the lack of cradle and rail make the device more reliable than existing launching systems.

3.2 Simulation

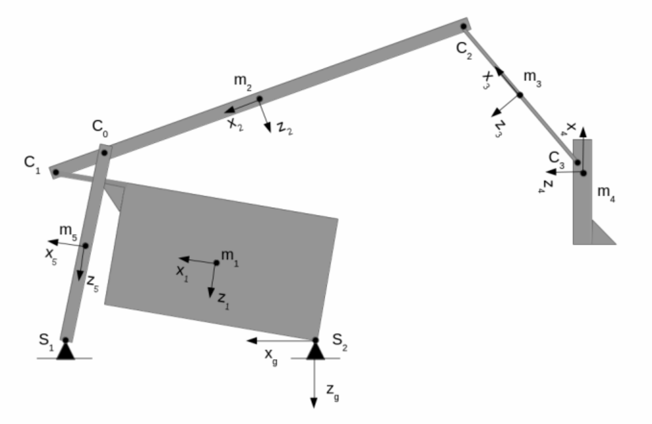


Fig. 8 Multibody model of the mobile trebuchet

The mobile trebuchet is a typical multibody system, which theory is well known ([7]). This particular system contains five rigid bodies (Fig. 8). Body m_1 is the transport vehicle. Only one of its axle supported by the ground (S_2), while the other is elevated from it by a force in the retrofitted connection point C_1 . Body m_2 is the trebuchet arm, while m_3 is the sling. Body m_5 is the support rod connected to the main pivot C_0 of the arm m_2 and supported by the ground in connection point S_1. These and all other connection points are modeled by an ideal pivot. Each body in the multibody system is affected by its own gravity and the forces in the connection points. The UAV (m_4) is the only body we expected to be exposed to the aerodynamic forces, too.

The impulse equation and the momentum equation were formulated for each body in its own body fixed coordinate system. The constraints in the connection points are modeled by an ideal pivot that prevents relative translation, thus it forces the acceleration of both connected body points to be equal. The two support points (S_1, S_2) are special connection points, where one of the bodies is the fixed Earth, thus the acceleration of the other body in the support point equal to zero.

Aerodynamic forces and moments on the UAV was calculated based on aerodynamical coefficients (lift coefficient C_L , drag coefficient C_D , moment coefficient C_m) provided by the XFLR5 software ([8]) for a typical UAV in the class of 10 kg. The angle of attack is calculated in each timestep of the simulation based on the motion parameters of the body m_5 representing the UAV.

Finally the equation system consists five impulse equations and five momentum equations according to the five bodies in the system and six constraints equation according to the four connection points and two support points. The rearranging of the equations results a differential equation system in the following form:

$$\underline{\underline{A}} \cdot \underline{\dot{x}} = \underline{b}(\underline{x}) \tag{1}$$

,where the vector of the first derivatives of the unknowns ($\underline{\dot{x}}$) contains the first derivatives of the following values for each of the five bodies :

$\underline{{}_iV_i}$	: velocity of body i in its own body fixed coordinate system
$\underline{{}_i\Omega_i}$	: angular velocity of body i in its own body fixed coordinate system
$\psi_i, \theta_i, \varphi_i$	: Euler angles of body i
$\underline{{}_iP_i}$	: position of the CG of body i in its body fixed coordinate system

and additionally the four reaction forces in the four connection point and the two reaction forces in the two support point. These forces have been included in the vector of the first derivative of the unknowns in order to be able to calculate the value of each unknowns in one step. This way the left division of both sides of (1) with the numerically calculated inverse of the system matrix $\underline{\underline{A}}$ resulted the value of each unknown. Subsequently we applied the above mentioned Runge-Kutta solver to integrate the relevant parameters in the vector of unknowns.

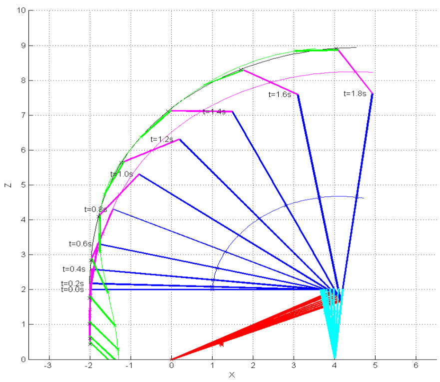
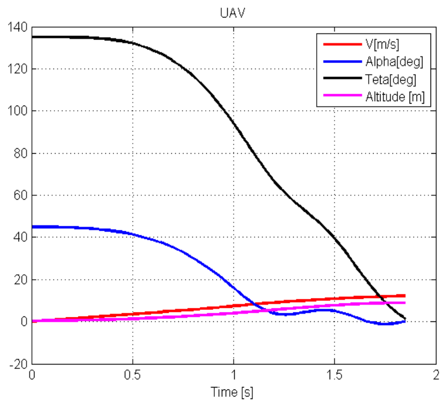
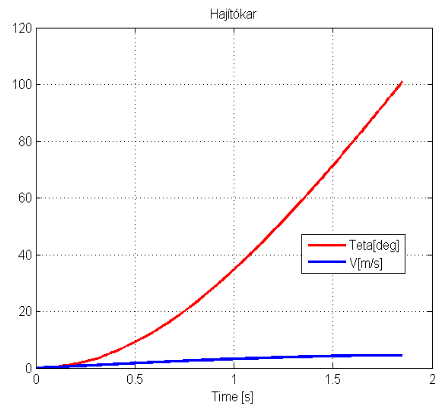


Fig. 9 Simulation of the mobile trebuchet

Fig. 9 shows a typical launch sequence of the mobile trebuchet. The green line represents the UAV, the magenta line is the sling, the blue line is the arm, the cyan line is the support rod. The transport vehicle is represented by the red line connecting the axle supported by the ground (left end) with the retrofitted connection point (right end).



a,



b,

Fig. 10 Parameters of the UAV (a) and arm (b) during launch

The simulation provided all of the important unknowns and enabled the investigation of the conditions at the release of the UAV. This way we could perform extensive analysis of the effect of UAV parameters such

- Center of Gravity
- position of release hook
- elevator deflection
- wing loading
- drag polar
- initial position and attitude

of the airplane in addition to the parameters of the trebuchet mentioned in Chapter 0 on the flight path angle, velocity, acceleration, angle of attack of the UAV during the launch and additionally the proper timing of its release from the arm.

3.3 Full scale test launches

The successful simulations proved that the mobile UAV trebuchet is feasibly, thus we started the development of the device. The first full scale version was designed intentionally oversized in order to be able perform launch tests with different position of the main pivot in the trebuchet arm. We've chosen an old fashioned VW Transporter as transport vehicle (and counterweight) because its robust and accessible frame is ideal for the additional fittings. In addition it provides enough volume for crew and test accessories.

During the first test campaign we changed the arm ratio step-by-step in order to increase the acceleration moment in reasonable steps and tested the device with projectiles. After we validated the simulation and found the setting for launching a projectile with the desired weight, speed and flightpath, we continued the tests with different freeflight and RC airplanes in order to validate the aerodynamic model.

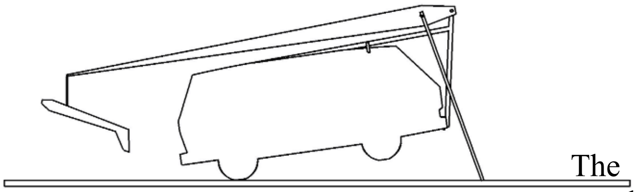


Fig. 11 Layout of the full scale test launcher

Fig. 12 Launch sequence

3.4 Prototype

After the promising tests with the full scale mobile trebuchet we decided to develop a prototype, which parts can be folded on the top of the transport vehicle in order to be allowed to drive on public roads with but can be installed by a single person in 5 minutes. We analysed several type of cars to find an optimal transport vehicle for the UAV system and for the launching trebuchet. In order to fulfil the regulations valid on public roads, and the requirement for the quick installation, we had to rearrange the original layout of the mobile trebuchet. The arm became shorter to compensate the less weight of the new transport vehicle, that caused the change in the launch direction, too. To eliminate dangerous parts of the supporting structure during a potential accident on the road, the arm support structure was replaced on the back of the car. The power for the installation and the arming of the trebuchet is provided by a commercial automotive winch mounted on the top of the vehicle.

The prototype was built and we are using it regularly to launch a UAV with 10 kg of takeoff weight.

Fig. 13 Prototype launches a V-tail, twin engine UAV

Fig. 14 Prototype in transport configuration

4 Conclusion

The goal of the project was to develop a launching device capable not only accelerate the UAV but release it in a safe altitude. We performed feasibility studies, multibody simulations, small scale and full scale tests in order to find an optimal solution. Finally a novel solution has been emerged, that is even more simple and reliable than existing UAV launching solutions in addition to the unique high release feature. The patent pending operational product prototype was built and is in use to support preparation of the serial production.

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