Winch Automation Proposal

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This document presents a revised proposal for a highly automated winch for glider launching. It is based on learnings described in a series of papers listed at the end of the document, most by the author, and comments and suggestions from reviewers of earlier versions. The author is grateful for their contributions – the proposal has benefited greatly. This proposal envisions a winch control system that provides extensive launch automation yet also makes provisions for keeping the human winch driver “in the loop” by providing intuitive options for modifying the launch program should that need arise and for handling emergency situations.

The series of papers represent a journey for the author and some proposals in earlier papers were modified or revised in later papers as new aspects of winch launching were better understood. The first paper in this series [1] demonstrated that maximum altitude attained, highest safety, and a better pilot experience would be provided by a winch that maintains constant tension in the cable during the climb phase as compared to other control schemes. Under tension control, the cable speed is free to change in response to the position of the glider in the launch, the pilot inputs, and meteorological events (e.g. thermals, gusts, windshears, downbursts). A major factor in the improved pilot experience, when operating under constant tension, is that airspeed control remains normal, i.e. pull back to slow, push forward to speed up. Inverted airspeed control occurs under some other methods. Investigations in a later paper [7] developed the basic servo control algorithms for a winch to accurately realize this tension control. However, what was found to be most difficult to control was the portion of the launch associated with the rotation.

The last two papers in the series developed and refined a recommendation that the winch control the cable speed in accordance to a predetermined profile during the ground roll and initial rotation. The automation design proposal presented in this paper is consistent with the further refined proposal contained in the last paper of the series [9] that serves as the basis for this automated winch scheme.

This is a winch automation proposal, not an automated winch proposal. This proposal is based on a single drum, hydraulic drive concept. The hydrostatic approach is the simplest to automate and the easiest for most to understand allowing the focus of this paper to be on automation, not dealing with the vagaries of different drive systems. The hydrostatic transmission, with its Continuously Variable Transmission (CVT) aspect, makes for a simple, elegant solution. This automation proposal can be readily adapted for an electrically driven system and, with somewhat more effort, a more classic Internal Combustion (IC) drive system. The additional effort required for the IC drive system has to do with the fact that some sort of fluid coupling is required, no reversing and braking capability is intrinsic, and the possible need to employ a multi-ratio transmission to match the speed-torque characteristics of an IC engine to the application. A diesel driven, fixed gearing winch will generally be easier to automate than a gasoline driven winch due to the flatter torque-speed characteristic. With minor modifications the design would be compatible with retrieve winching and is readily extensible to multiple drums.

I am open to working with any group in adapting this proposal to an actual winch project. I will be proposing a prototype winch controller development as a senior engineering student project for a local university beginning this fall. This proposal would serve as the starting point for the project. It is hoped that the resulting design, software and hardware, could be readily applied to a real project.

The outline of the presentation is as follows. First a winch system model is described that serves as the "plant" for the automation development. The next section describes the operator interface to the winch. The winch operator's primary input is through a control lever whose operation is intuitive but varies with the particular launch phase. Other inputs and outputs are described in this section as well. The next section introduces an automation state machine which determines the system behavior during the various phases of a launch. The progression of states during a nominal launch is described illustrating how the operator and automation system would interact under ordinary conditions. Following this description, a much more detailed examination of the states and the conditions, both normal and abnormal, that result in transitions between states is presented. The body concludes with a short discussion of the software development environment. An Appendix contains some additional technical descriptions referenced in the text. These last detailed sections are optional for the reader who only desires a general understanding of operation under an automated system.

While this is moving towards a requirements document, it is a still a proposal and review, comments, and alternative suggestions are strongly encouraged. Foremost in every reviewer's mind should be maximizing safety. The author believes the safety of winch launches will be augmented by the proper automation of the launch process under the careful supervision of the winch operator. The winch operator must always have final authority over the winch operation. Every conceivable eventuality that may occur during any phase of the launch must be considered and safeguards and redundancy incorporated to minimize the potential of damage or injury.

High Level System Description

Figure 1 is the model used to develop this automation proposal. The key elements are now described and their functions will be expanded on in the discussions to follow.

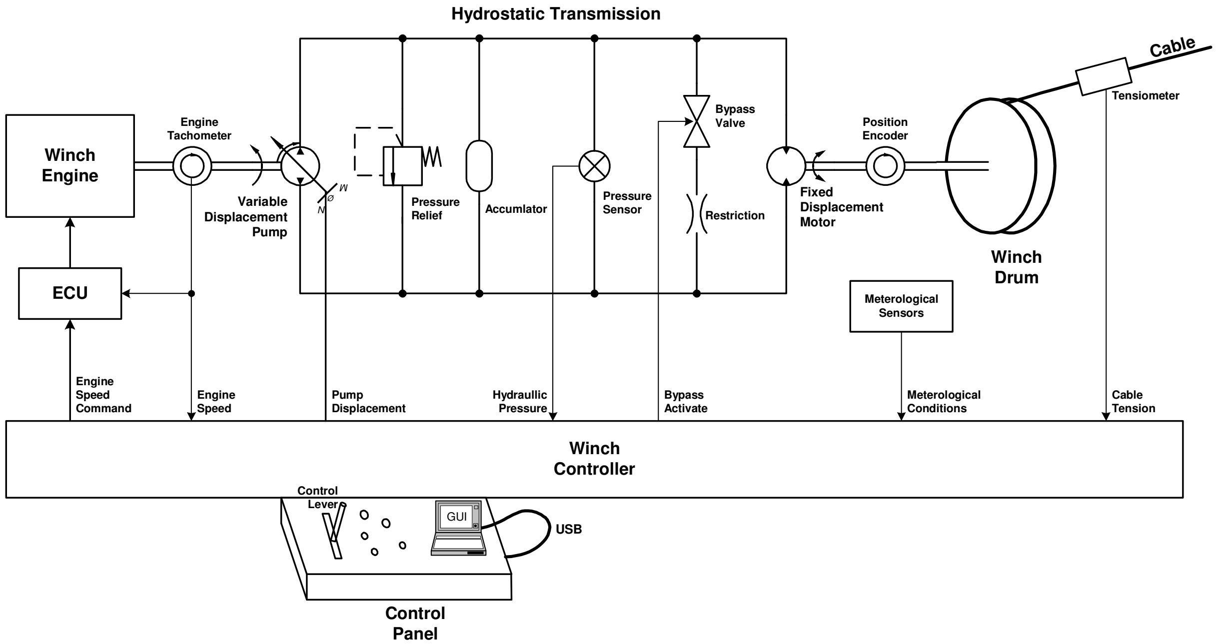

Figure 1. High Level Hydrostatic Winch Model.

The prime power source for the winch is the Winch Engine. It is most likely an IC engine but the CVT capability afforded by the hydrostatic transmission only requires it be able to produce the required power at a single fixed speed. Whether it is diesel, gasoline, or electric is of little importance for a hydrostatic winch. It normally will operate at only 2 speeds, idle and nominal operating speed. The operational speed should be that where the engine is capable of producing its maximum power.

The ECU is the engine control unit for this engine. It adjusts the throttle to hold the engine at the commanded speed. The engine tachometer measures the shaft speed that the ECU employs in a feedback loop to hold the speed at the commanded value. This measurement is also provided to the Winch Controller but its primary function in the controller will be to monitor that the engine is operating within some tolerance of the desired value. A large flywheel may be of value to smooth transient events and to aid braking as will be discussed later in the paper.

The engine drives the variable displacement pump, the input to the hydrostatic transmission. This is a very simple depiction of such drives but is hopefully sufficient for the primary purpose of this paper, automation of the launch. Reference 7 describes hydrostatic drive systems in more detail and investigates controlling cable tension in such systems using feedback controls. That analysis suggested a PI controller is appropriate for this task but further discussion of that aspect is not relevant to this presentation. The pump displacement is varied by the winch controller and is the primary command input to the drive system. Both positive and negative displacements can be commanded. In a kiting situation and some ground handling the drum can actually rotate backwards.

A pressure relief valve protects the system from excessive pressures if there is a failure in the controller. Also shown is a small accumulator. Whether or not the accumulator is actually needed is not clear but some slight compliance in the system will minimize shock loads to the system due to the incompressible nature of the hydraulic fluid. This accumulator also limits overpressures before the relief valve functions. A pressure sensor is provided for measuring the differential pressure across the hydraulic motor. This is a measure of the torque being provided to the drum and may also be used to effect limiting in the control system such that the relief valve does not need to function under high dynamics due to the servo system calling for torque (pressure) beyond the system capabilities. The pressure relief valve should not need to be activated in a properly implemented system.

An electrically activated bypass valve in series with a flow restriction is used during ground handling phases to make the system friendlier for ground personnel. It “softens” the hydrostatic transmission behavior during the ground preparation phases of the launch simulating a fluid coupling. Further discussion of its function is provided shortly.

The fixed displacement hydraulic motor completes the hydrostatic transmission. Its output shaft drives the drum, possibly through a fixed ratio gearbox (not illustrated). A position encoder measures drum position and may be differentiated to calculate drum speed. The cable speed can be inferred from this value when the cable radius on the drum is estimated. A more direct measure of the cable speed also can be realized by placing a tachometer on a pulley in contact with the cable. Even if direct cable speed sensing is available, a drum tachometer function will still be very desirable as a break in the cable could disable the direct line speed measurement. These are second order details and are again not fundamental to the basic automation discussion. They are very pertinent to failure modes analysis.

Key to high performance launches is the ability to accurately control the tension in the cable. To close a feedback loop around the cable tension, a tensiometer is employed to measure the cable tension. As discussed in Reference 3, the drum and cable inertia can cause significant deviations in the cable tension when using the simplistic *tension equals torque/radius* relation. My base assumption is that this is a Running Line Tensiometer (RLT) but other methods have been proposed. Again the actual tension sensing method is not critical to the discussion at hand.

A box representing meteorological sensing is shown. The primary purpose of these measurements is to determine the headwind component to modify the launch profiles accordingly. In addition, the measurement of temperature and pressure to compute density altitude can also provide valuable corrections between true and indicated airspeeds. Ideally the wind conditions would be measured near the liftoff point and remoted back to the winch for near real-time adjustments to the launch profile. Knowledge of wind conditions during the rotation are the most critical for providing a safe, high performance rotation. Once in the climb, constant tension control automatically adjusts for varying meteorological conditions.

The operator provides inputs through a Graphical User Interface (GUI) and control panel inputs. The primary control input for the operator during the launch is a control lever. Further expansion on the control lever and other operator inputs is contained in the next section. The control panel and GUI also provide information to the operator concerning the winch operational state and the parameters being employed for the launch, e.g. glider, pilot, headwind, tension factor chosen, … The GUI will likely be implemented on a laptop or PDA computer. A keyboard can be useful for data entry as well. The likely candidate for connecting this computer to the winch controller is a USB cable. While the GUI is employed as an input device to provide launch specific parameters to customize the launch, this processor is not involved in controlling the actual launch. During the actual launch, the winch controller has full control of the system. The winch controller will be based on an embedded microprocessor and sequences the system through the launch phases while executing the different feedback control laws.

Winch Inputs and Outputs

Control Lever

The primary operator control input during the launch is the control lever. To the uninitiated, this may first appear to be a simple throttle. In fact, as proposed in this document, it is a great deal more than that. Embedded intelligence will act as a "guiding hand" to the winch driver assisting him in delivering consistent, superior launches in the face of varying environmental conditions and pilot behaviors.

Once the system is armed, the operator inputs to the system are normally only through this input until cable recovery is complete. The system behavior in response to these inputs is described in more detail in the following section providing a typical launch sequence overview.

The control lever is constructed to allow the winch operator to generally know where the lever is positioned without the need to look at its position. This is realized by a mechanical system that employs springs and hard and soft stops. Figure 2 illustrates the force required (solid trace) to displace the lever through its operating range and the input (dashed trace) provided to the control system as a function of this displacement.

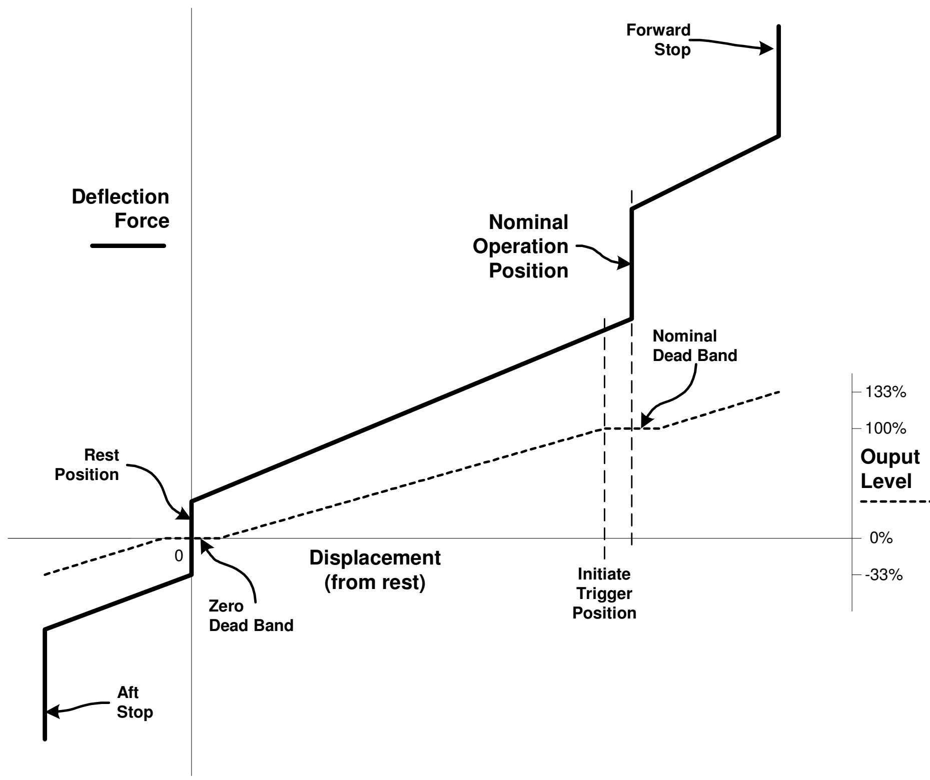

Figure 2. Control Lever Operation.

This is a very technical way of describing an input device with a hands-off rest position and a Nominal Operating Position detent that can be pushed through with additional effort. With no operator input, the lever reverts to the indicated Rest Position.

Forward or reverse displacement of the lever from the Rest Position does not occur until the force magnitude exceeds the indicated detent step value. Once this magnitude is exceeded, the lever advances (or retards) linearly with increasing force. In the reverse direction this deflection increases until the Aft Stop is reached. In the forward direction the deflection increases until the Nominal Operating Position is reached. Further deflection does not occur until the force is further increased by an additional detent step value. When the force has increased by this second step amount, the control lever deflection again increases linearly with increasing force until the Forward Stop is reached.

As will be described shortly, the actual launch automation sequence is initiated by advancing the lever to the Nominal Operating Position. Under normal conditions, the lever is held at this position until it is time for the winch operator to signal the pilot it is time to release by retarding the lever to reduce the cable tension from the predetermined target climb tension level.

During different phases of the launch, the control lever position provides different inputs to the system but, during a normal launch, the control lever will nominally remain at the

Nominal Operating Position detent. It can modify predetermined profiles and target values at the operator's discretion by deviating from this nominal position. In some phases its primary control function is cable speed and in others it is cable tension. Generally the Rest Position represents 0% and the Nominal Operating Position signifies 100% of the profile or target value. Values greater than 100% of the predetermined values are signaled by advancing beyond the Nominal Operating Position.

Retarding the lever below the Rest Position is primarily employed to increase braking action. To preclude the cable slipping and fouling, deceleration is normally limited. Moving into the negative range progressively increases the braking action if needed for a rapid stop. During the preparation phase retarding the lever into the negative range will reverse the drum but this capability should be rarely needed.

The dashed response is the input to the winch controller as a function of deflection. There is a dead band around the Rest Position where the input to the system is zero. This is to accommodate sensor zeroing errors and to establish a definite zero region to reduce the potential for creep. During some portions of the launch, retarding the lever into the Rest Position dead band aborts the launch sequence. This dead band insures releasing the lever always generate a zero output in the presence of position sensor inaccuracies.

Moving out of this dead band, the input to the system increases linearly such that 100% corresponds to the Nominal Operating Position. Further forward deflection increases the input to a maximum value at the Forward Stop position. The value indicated is 133% but the actual value is TBD. There is a small Nominal Operating Position dead band where the output is defined to be 100%. This is to accommodate position sensor errors and prevent small deviations from the Nominal Operating Position from varying the output. The sizes of the dead bands are TBD and depend somewhat on the position sensor accuracy and ergonomic considerations. For negative deflections the smallest output level indicated is -33% but the actual magnitude of that value is also TBD. The transfer functions depicted are mostly linear but non-linear transfer functions may also be employed to shape the response to better match the needs during different phases of the launch.

The control lever shall be mechanically damped to further smooth the operator inputs and reduce overshoot and ringing if the lever is moved quickly or released.

This input is further filtered with a non-linear smoothing filter. The non-linear aspect refers to slew-rate limiting employed to limit the rate of change of operator inputs. This is particularly important in certain speed controlled modes. The bandwidth and slew-rate limiting parameters can vary during different phases of the launch. Further discussions of such filtering and its realization are contained in the detailed RECOVERY state description and in the Appendix.

As indicated before, the actual launch sequence is initiated by advancing the lever to the Nominal Operating Position detent. Again, to accommodate sensor accuracy issues, the trigger level is actually slightly before the Nominal Operating Position as indicated by the

Initiate Trigger Position. Launch aborts are signaled in some states by the control lever returning to the Rest Position. The inputs employed for initiating state changes are not temporally filtered.

The lever position sensor is expected to be a quadrature incremental optical (probably rotary) encoder. The actual sensor output is linear with position but with scale and zero errors. Software will calibrate this sensor to the mechanical system and will effect any non-linear responses and the small dead bands to make sure improper operation does not occur due to small drifts after calibration.

Additional Operator Inputs

In addition to the input from the control lever just described, there are several other inputs that the winch operator employs. Some of these are ancillary to a normal launch and only a couple would be used in the normal launch process. These are briefly described below and their function will become clearer with the progressively more detailed descriptions in the following section. Ergonomic studies will be employed to determine the location and physical characteristics of these input devices as well as the control lever.

Master Switch

This switch is selected On to allow operation of the winch and Off to shut down winch operation. It will likely be a keyed switch and may have a Start position to engage the engine starter.

Active/Safe Switch

This switch is used to safe the system to preclude accidental operation of the winch. It may be thought of as putting the winch in neutral. In the Safe position, the engine can run but every effort is made to preclude drum motion due to the winch. It will be a prominent two position switch so that it provides a visual winch status indication.

Arm/Disarm/Abort Pushbutton

When all ground preparation is complete and the pilot is ready, the operator pushes this button to arm the system for launch. Pressing this button brings the engine up to operational speed. Once armed, moving the control lever to the Nominal Operating Position initiates the launch sequence.

Pushing the button while armed will toggle the system back to a state employed to prepare for the launch which includes returning the engine to idle.

After the launch has begun, activation of this pushbutton will transition the system to a state where the operator has direct speed control of the drum via the control lever. Use of this aborting action is expected to be very rare as simpler means are provided to effect the same transition (return the control lever to rest) and aborts should be rare in the first place.

Retrieve/Prep Pushbutton

After cable recovery following the glider releasing the cable, this button is pressed to condition the winch for cable extraction by the retrieve vehicle. Pressing this button again transitions the winch into a state intended for the final ground preparation (cable hookup, take up slack) for a launch. Subsequent activations of this button toggles the winch between these preparation and retrieve winch modes.

Emergency Guillotine Actuator

This actuator will fire the Guillotine to cut the cable in an emergency. In the interest of safety and redundancy, this function should be independent of the software based solution for the general automation implementation – preferably a simple mechanical release. That said, a switch sensing this activation should send a signal to the automation system indicating the activation. This should be treated at least as an Abort if not an Emergency Off indication.

Emergency Off Pushbutton

This very prominent pushbutton is employed to shut down the winch in an emergency. It will be of the type that requires a manual reset once the button is activated. The primary purpose of this switch is to shut down the winch if the control system locks up or goes berserk. It is mandatory that this function operate even if the software system has locked up in the interest of safety. Most likely this function will simply remove power from all elements of the winch. The power off condition of every winch element must be considered such that the most graceful and non-damaging transition to an inert state will result if this occurs when the winch is operating.

Motor Start Pushbutton

This button is used to engage the engine starter if it is not included in the Master Switch.

Motor Stop Pushbutton

This button is used to stop the engine.

GUI

A graphical user interface via a notebook PC and/or PDA (TBD) will be provided to allow the operator to input information necessary for the launch. The GUI is the primary means for entering the information necessary to parameterize the winch controller for an upcoming launch. This information includes information like the glider, the pilot, the pilot's requested launch characteristic (e.g. mild, moderate, aggressive), and glider weight (particularly when it can carry ballast).

If automated meteorological measurements are not part of the system input, the GUI or keyboard will be used to input wind speed, direction, temperature, pressure …

Rather than have the operator enter the details that are required to properly parameterize the winch controller for each launch (e.g. glider stall speed, maximum tension factor, glider weight, maximum winching airspeed), the GUI will contain a database of this information for each glider/pilot combination. In most cases the operator will simply select the appropriate combination from displayed lists of gliders and pilots. As noted, the launch characteristics may be adjusted from mild to aggressive to tailor the flight to the pilot's preference. For example, a pilot taking a nervous passenger for a first flight might request a mild launch. Students or pilots new to an aircraft will begin with mild profiles and progress to more aggressive launches as their experience and conditions permit.

The GUI also will be used to display and log the behavior of the winch and meteorological conditions (if available) during the launch. Information logged includes cable speed, cable tension, sequencer state, meteorological conditions, engine parameters, hydraulic pressure, control lever position, button activation points, cable draw, and any abnormal conditions encountered during the launch. During the active portion of a launch the operator should be focused on the glider, not looking at the control panel. This logged data may be used for later review by the winch operator and/or pilot. This display and logging will be useful as a training aid for pilots and operators and will allow refinement of the winch automation. Each launch will be uniquely identified and the data time-tagged.

The GUI and its associated processor have no control over the winch during the actual launch. Once these parameters are entered or reconfirmed for the launch, the winch controller is solely responsible for the winch sequencing and control under the operator's direction. Hence there are no hard real-time requirements for this processor.

Control Panel Outputs

The control panel will have outputs to aid the winch operator as well. These may include an indication of sequencer state and engine operating parameters, e.g. oil pressure, temperature. Some input buttons or switches will provide a visual indication of their state. An audible signal signifying important state changes is also employed. An engine hour meter may be included for scheduling winch maintenance.

Launch Automation Description

The launch automation process is illustrated by the high level state diagram of Figure 3.

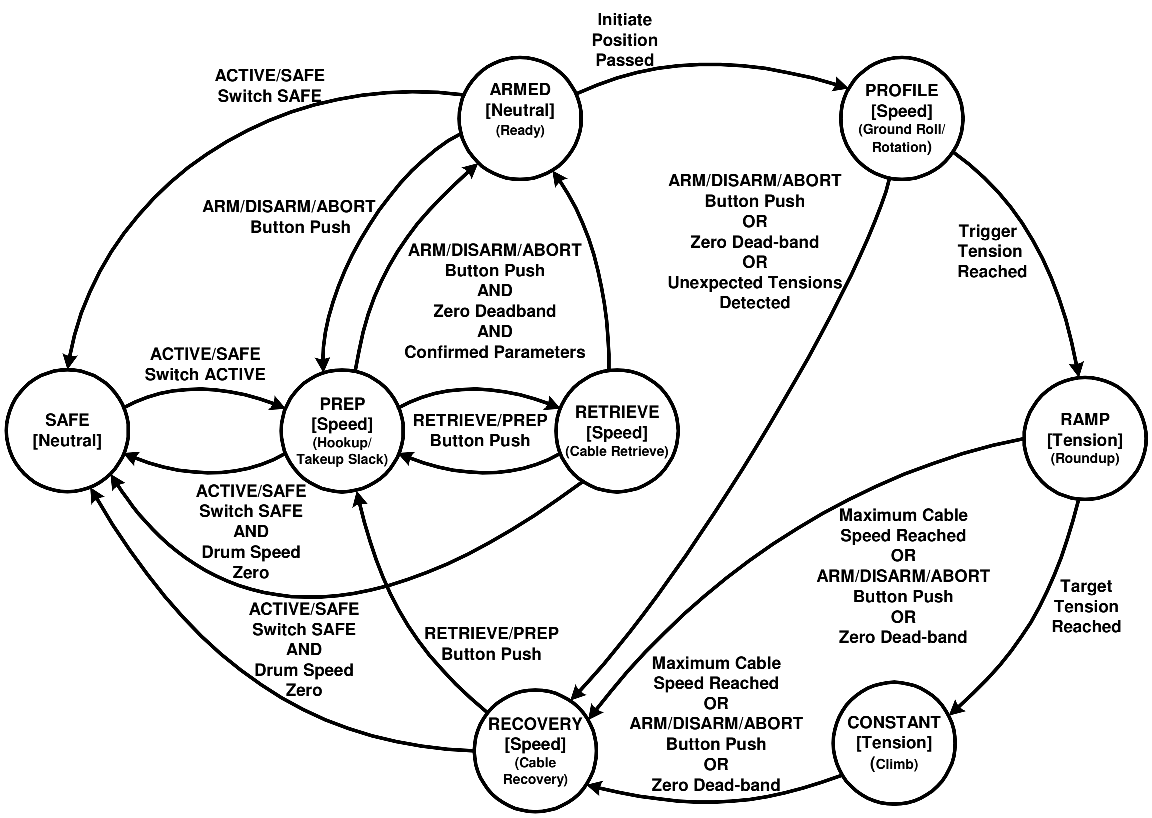

Figure 3. High-Level Launch Automation State Diagram.

During a normal launch sequence, the system cycles mostly clockwise around the circular ring of states beginning at the PREP state. A detailed description of each state and its behaviors in both normal and abnormal conditions is presented shortly. The amount of detail in these descriptions has the potential to obscure the basic behavior during a normal launch which should constitute the vast majority of launches. To avoid information overload, a short description of the operation under this state machine for a representative ordinary launch is now presented. The operator has the authority to modify the predetermined profiles and parameters for the launch by displacing the control lever from the Nominal Operating Position but discussion of this capability is again deferred to the detailed description of the behaviors in each state that follows.

Normal Launch Sequence

The system starts in the PREP state where ground handling and hookup are performed. In this state the operator can payout or take-up slack by moving the control lever backwards or forwards respectively. The bypass shunt circuit is active and approximates a fluid coupling so that the ground handlers can easily stop or pull the cable out of the winch during hookup even if the control lever is in the Rest Position.

The operator selects the glider and pilot from a database using the GUI and what type of launch he desires (e.g. mild, moderate, aggressive). The system uses this information, along with the meteorological information, to compute the profiles and parameters to be used for the launch. When the launch is imminent, the operator presses the ARM button and the system advances to the ARMED state.

In the ARMED state the winch engine is brought up to operational RPM. When the pilot signals ready, the operator advances the control lever to the Nominal Operating Position transitioning the system into the PROFILE state.

The PROFILE state initiates the launch following a pre-determined cable speed profile based on the glider, pilot, and meteorological conditions. Figure 4, from Reference 8 (Figure 14), depicts the cable tension factor, the glider airspeed, the cable speed, climb angle, and glider altitude during a highly idealized (no drag or friction considered) launch in no wind.

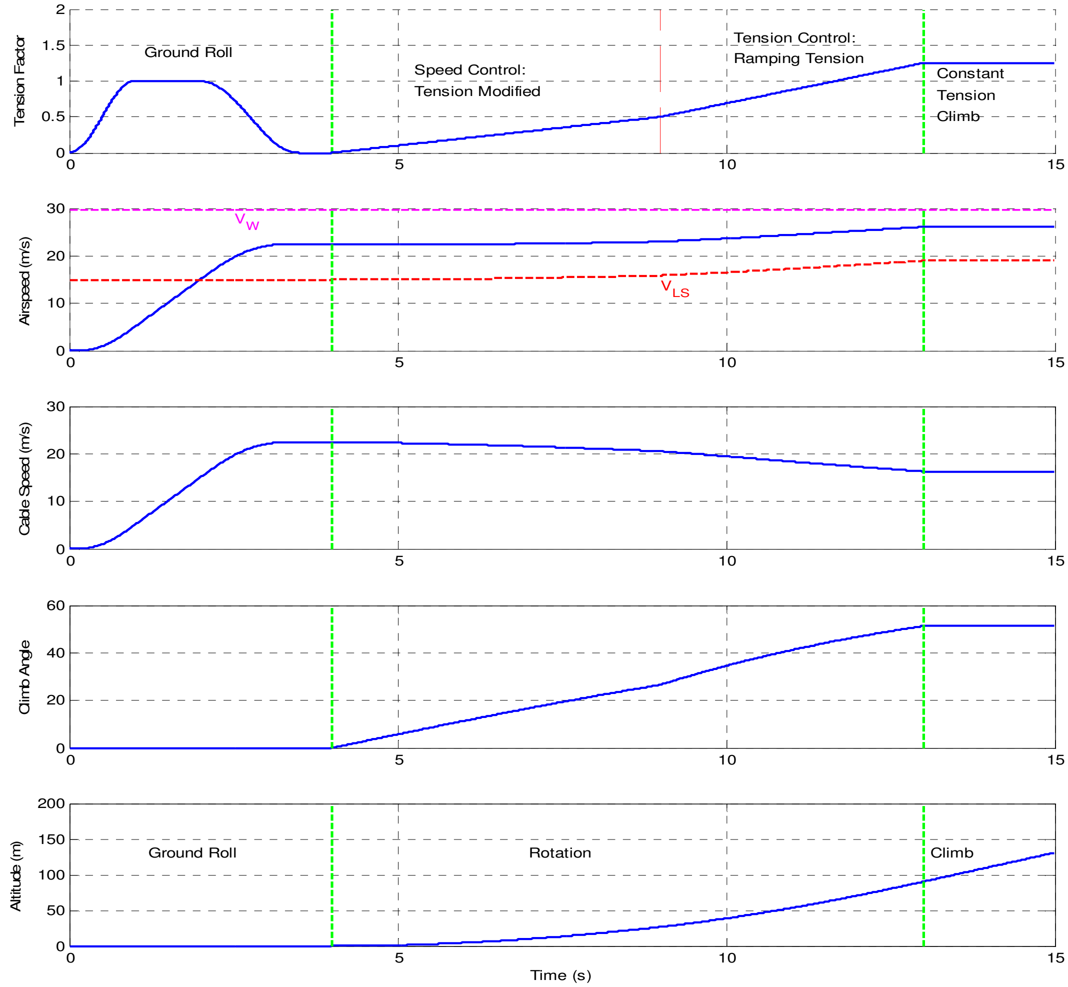

Figure 4. Normal Launch Speed/Acceleration Profiles.

The cable speed is seen to increase smoothly with increasing acceleration until a maximum acceleration is reached (in this case about 1G). This acceleration level is held until the cable speed approaches a predetermined target value of about 1.5 V_s. Shortly before this speed is reached, the acceleration is smoothly reduced to zero such that the cable speed stabilizes at this target value. (The figure depicts a slight cable slowing during the early rotation but this was changed to constant speed in the last paper of the series [9].)

The pilot lifts off at about 4 seconds into this launch and continues to rotate increasing the climb angle. The rate of rotation is solely at the pilot's discretion. As he rotates, the tension in the cable rises along with a slight increase in airspeed. When the tension factor reaches a predetermined trigger value, 0.5 in this example, the system transitions to the RAMP state at about 8 seconds into this simulated launch. The pilot in this example was depicted as delaying the rotation to show the behavior of the automation sequence should this occur. In practice, rotation could begin even earlier while the glider is still accelerating.

In the RAMP state, the winch switches from speed to tension control of the cable. The tension starts at the tension trigger value and the controller smoothly increases the tension to the target climb tension factor value over several seconds. The climb tension and how quickly the ramping occurs are primarily determined by the type of launch requested; mild, moderate, aggressive. In this example, the final climb tension factor is 1.3 and the ramp lasts 5 seconds. (The climb tension level would be generally considered moderate to aggressive but the rotation rate is rather mild.) As the tension increases, the pilot continues the roundup to keep his airspeed from rising excessively. The system transitions into the CONSTANT state as the tension ramp completes 13 seconds after the launch began.

The system remains in the CONSTANT state for the remainder of the climb (not illustrated). While in this state, the cable tension is held constant at the target tension value. As the glider approaches the top of the launch, the winch operator reduces the cable tension by retarding the control lever from the Nominal Operating Position. The pilot, sensing his airspeed dropping, lowers the nose and quickly recognizes it is time to release. How fast and how far the tension is reduced is wholly at the discretion of the winch operator. The pilot releases and, for him, the launch is over. Since the launch began, the winch operator simply held the control lever in the Nominal Operating Position until it was time to signal the pilot it was time to release.

This concludes the mostly automated portion of the launch but the winch controller and operator still have to deal with the cable recovery. When the operator confirms the release, he advances the control lever back to the Nominal Operating Position. The winch, still in tension control, wants to hold the tension at the target value. With the glider released, the cable accelerates rapidly until it reaches a predetermined maximum speed, generally around V_w for the glider. Reaching this maximum cable speed triggers the system transition to the RECOVERY state. This rapid acceleration quickly pulls the parachute away from the glider to preclude a collision with the parachute.

In the RECOVERY state, winch operation reverts to cable speed control with the Nominal Operating Position corresponding to this maximum cable speed. The operator now uses the control lever to control the cable speed. He flies the parachute to the winch or lets it fall to the ground stopping the drum by retarding the control lever to the Rest Position.

After a short cool down period for the engine at the operational RPM, the operator pushes the Prep/Retrieve button transitioning the system to the PREP state where the engine is returned to idle and the bypass value is opened. When the retrieve vehicle has attached the cable to the hitch, the operator pushes the Retrieve/Prep pushbutton again to transitions to the RETRIEVE state. The only difference between the RETRIEVE state and the PREP state is that a slight tension is established in the cable. This bias keeps the drum from overrunning when the retrieve vehicle slows. When the retrieve is complete the operator pushes the Retrieve/Prep pushbutton again to transition the controller into the PREP state. This completes a normal launch cycle and we are ready for the next glider hook up.

Note that the winch operates under speed control during the RECOVERY RETRIEVE, PREP, and PROFILE states. It operates under tension control during the RAMP and CONSTANT states. The system is essentially in neutral while in the ARMED and SAFE states. This is indicated in the state diagram by the bracketed terms indicating the primary control mode while in each state. During a active launch phases, the system only transitions between speed and tension modes once – it starts in speed, transitions to tension and stays there until the pilot releases. Then the system returns to speed control for recovering the cable.

Detailed State Descriptions

The following are more detailed controller state descriptions. The remainder of this paper is optional for the reader only interested in a high-level understanding of the automation proposal. Here both normal and abnormal (cable breaks, aborts) launch scenarios are considered. Most of these states are actually superstates and contain sub-states that govern their detailed behavior. Additional definition of the behavior of each sub-state will be needed as the design progresses.

It is imperative that reviewers and designers of this system consider every eventuality that may occur at any time during the launch and determine the best course of action for the controller to give the operator and pilot the greatest opportunity to deal with the situation safely. The question "what if?" should be asked at every opportunity. As these descriptions are read, imagine everything that could go wrong and see if the behavior proposed deals with the situation most effectively. If not, please identify overlooked issues and/or suggest alternative solutions to the author.

SAFE

This superstate corresponds to the condition when launching is not active. It is the initial state on power up. It is in this state that the engine is started and warms up. The engine may not be started unless the Active/Neutral switch is in the Neutral position. While in this state the pump displacement is held at zero and the hydraulic bypass circuit is switched into the system to minimize any creep or tension due to imperfect pump displacement zeroing. Further discussion of this bypass circuit is presented in the PREP state description. Control lever actions have no effect in this state. In essence, the winch is in "neutral " when in this state.

If the winch has a bystander warning system, e.g. rotating yellow lights, they would be off in this state and on in all other states. A short audible signal could be emitted prior to departing this state for PREP state. The transition would be delayed until the audible signal has completed.

The Active/Safe switch must be moved to the Active position in order to enter into the PREP state to prepare for a launch. If this switch is returned to the Safe position the system will return to the SAFE state as soon as the winch drum velocity is zero AND the system is in the PREP, ARMED, RECOVERY, or RETRIEVE states. Requiring the drum speed to be zero prevents putting the winch in neutral while the drum is in motion. Transition to the SAFE state from PROFILE is not allowed as the drum speed should never be zero in this state (ignoring the initial entry condition). Transition from the tension controlled states, RAMP and CONSTANT, are not allowed as it is plausible for the cable speed to reach zero under the unusual but possible kiting conditions.

There can be numerous sub-states of this superstate. Examples might be MOTOR OFF and MOTOR ON sub-states. The operator will press a MOTOR START button (or turn the Master switch to Start) to signal the system to move from the MOTOR OFF sub-state to the MOTOR ON sub-state possibly via a MOTOR STARTING sub-state. The system can only transition to the PREP state from the MOTOR ON sub-state. When the key is returned to the SAFE position, the system will normally return to the MOTOR ON sub-state. An exception would occur if the motor had died. Then the system will return to the MOTOR OFF sub-state. A MOTOR STOP button will signal the system to transition from the MOTOR ON sub-state to the MOTOR OFF sub-state. Pressing the MOTOR START button or MOTOR STOP button is ignored when in other states. If an audible warning transition is provided, there will be a WARNING state where the signal is active prior to the transition to the PREP state.

Activation of the EMERGENCY OFF button in any state will immediately kill the engine. This mechanically sticky button must be manually reset for normal operation to be reestablished. There are no transitions shown in the state diagram as this action is expected to kill all electrical power to the winch controller.

PREP

The PREP superstate is where the system normally resides in preparation for a launch. In this state the engine is at idle and the control lever controls cable speed but only over a limited range, e.g. 5 m/s.

The maximum tension that the system can produce will be limited in this state by switching in the hydraulic bypass circuit. This shunt circuit will contain a restriction that is sized such that the torque, and hence tension, is limited by the peak pressure that will result with the allowed pump displacement (might not use full authority). This peak tension, e.g. 25 lbf, will be such that a line attendant can readily stop or reverse the cable motion by bracing against the cable or the glider by applying the wheel brake.

The normal transition out of this state during a launch is to the ARMED state and occurs when the operator pushes the ARM button AND the control lever is in the zero dead band region AND a new or reconfirmed set of launch parameters has been selected.

Pushing the Retrieve/Prep pushbutton transitions the winch to the RETRIEVE state which is usually employed for retrieving the cable. The RETRIEVE state may also be used as the precursor to the ARM state. Repeated activations of this pushbutton toggles the system between the PREP and RETRIEVE states. The system can also be moved back to the SAFE state by switching the ACTIVE/SAFE switch to the Safe position but the transition will not occur until the drum has stopped.

The controller servo system could emulate the bypass valve behavior employing feedback from the pressure sensor. This is not developed much further here to keep the focus on automation and not implementation variations. Whether or not to actually have the bypass valve or to emulate it may be reconsidered in the future as a better understanding of failure mechanisms evolves. If different restriction values are required for the RETRIEVE state, the selectable restriction could be emulated using such pressure feedback. This would retain the failsafe characteristics of a physical bypass valve but lower the cost and allow fine tuning of the effective restrictor size in different states.

In the event of an Emergency Off shutdown, failsafe features associated with the bypass valve and pump actuator need to be considered. With no electrical power, this value should be open to avoid high pressure buildup in the hydraulic circuit and the associated high acceleration/deceleration of the drum. Similarly the pump displacement actuator should nominally move to the zero displacement position on loss of power to isolate the engine from the hydraulic drive system.

ARMED

This superstate is entered immediately before the launch is initiated. The engine is taken to operational RPM. The pump displacement is zeroed in this state independent of the control lever position. The hydraulic bypass circuit remains active to preclude cable creep due to imperfect zeroing. The transition to the PROFILE superstate occurs when the control lever is advanced past the Initiate Trigger position AND the engine has reached operational RPM.

If real-time meteorological updates are available, parameters for the launch may be updated until entry into the PROFILE state.

Pushing the ARM/RESET/ABORT pushbutton transitions the system back to the PREP state. Note that the winch operator must reconfirm or reenter new launch parameters before the system may be advanced back to the ARMED state after such a reset action. The system can be moved back to the SAFE state by switching the ACTIVE/SAFE switch to the Safe.

An alternate behavior that could be implemented would be to allow active cable tensioning in this state. Advancing the control lever would progressively increase the tension. The amount of tension that could be developed would be limited by the control lever scaling and the fact that the bypass value is active. Comments?

PROFILE

The PROFILE superstate covers the ground roll and early rotation phases of the launch. A preprogrammed cable speed profile is followed, the parameters of which determined by the glider characteristics and configuration, pilot preferences, and meteorological conditions.

The speed profile is designed to smoothly increase acceleration to a predetermined constant acceleration value, hold that constant acceleration until the cable has reached a speed near a target speed (e.g. 1.5 V_s - Headwind [component]), and then smoothly decrease the acceleration such that the cable speed reaches the target speed just as the cable acceleration reaches 0.

This cable speed is then held constant until the end of the state as will be described shortly. (Holding the cable speed constant during the early rotation was the slight modification (and simplification) between the proposed methods in Reference 8 and Reference 9.) The computation of the velocity profiles for raised cosine acceleration tapers are particularly simple. Further details and justifications for this profile are provided in References 8 and 9.

During the initial acceleration taper-up and the early part of the constant acceleration ground roll period (e.g. up to 0.8 · (V_s - Headwind [component]) of this profile, the cable tension is measured and compared to the expected tension plus or minus a tolerance factor, e.g. 15%. If the cable tension exceeds these limits, the launch is aborted and the system transitions to the RECOVERY state. Such a deviation could indicate a cable break (tension drops suddenly) or, more subtlety, incorrect designation of the glider or its weight. In essence, the glider is "weighed" during the initial acceleration period and the launch is aborted if the estimated weight differs from the expected weight by too much. This aborting function is disabled before the glider reaches flying speed to preclude dumping the glider just as it rotates. If aborted, the cable speed will be maintained on entry into the RECOVERY state (so long as the control lever remains at the Nominal Position) to reduce the probability of the glider flying into the deployed parachute should there be a weak link failure during this period. This is further discussed in the detailed RECOVERY state section.

As the glider lifts off and rotates, the tension is not simply determined by the force required to accelerate the glider mass (and overcome drag and rolling friction) as the wing lift begins to oppose the cable as well. As the glider rounds up, at a rate solely determined by the pilot, the cable tension increases. When the tension factor has increased to a predetermined value (e.g. 0.5), the system transitions into the RAMP state.

During the PROFILE state the cable speed profile is scaled by the control lever position – the Nominal Operating Position corresponding to 100% of the specified profile. The operator has the authority to increase or decrease this scaling factor by advancing or retarding the control lever from the Nominal Operating position. This could be in response to an observed meteorological disturbance or any other situation where the operator determines the cable speed needs to deviate from the predetermined profile.

If the operator pushes the ARM/RESET/ABORT button or retards the control lever into the zero dead band while in this state, the system will transition to the RECOVERY state where manual speed control is provided.

RAMP

In this superstate, the tension is progressively increases from the trigger tension value, which initiated the transition from the PROFILE state to this state, to the target tension value chosen for the climb phase. This progression occurs over a specified period of time. The profile may be as simple as a linear ramp but may be shaped (e.g. quarter-sine) to soften the final approach to the target climb tension.

The primary control mode in this state is of cable tension. The tension ramp profile (minus the target tension value) is scaled by the control lever position. The Nominal Operating Position corresponds to 100% of the ramp profile. This provides the operator the ability to adjust the tension profile based on the launch conditions. Again the need for the operator to deviate from the preselected profile should be very rare.

At the completion of this period, the cable tension will be at the (scaled) target tension value and the system will transition to the CONSTANT state. If the operator pushes the ARM/RESET/ABORT button or retards the control lever into the zero dead band, the system will transition to the RECOVERY state where manual speed control is provided. Also during this period the cable speed is monitored. Should the cable speed increase to a launch specified maximum value, e.g. V_w – Headwind (component), the system will transition to the RECOVERY state. One situation where this may occur is when there is a cable break. Another is when the pilot fails to rotate sufficiently to control his/her airspeed.

CONSTANT

This is the state corresponding to the launch climb phase where the tension is held constant at a prespecified target tension value. Again this target value is scaled by the control lever position with the Nominal Operating Position corresponding to 100%.

Under normal conditions, the winch operator will begin retarding the control lever when he determines the glider is nearing the release point. This will result in the tension in the cable diminishing. The pilot will see his airspeed begin to drop and will reduce pitch angle to counter this decay. As he continues to push over, the pilot will quickly realize the top of the launch has been reached and will release the cable. When released, the cable tension will drop and the control system will increase the cable speed in an attempt to reestablish the commanded tension. When the cable speed reaches the launch specific maximum value, e.g. again V_w – Headwind (component), the system will automatically transition to the RECOVERY state.

Just as in the RAMPING state, pressing the ARM/RESET/ABORT button or retarding the control lever into the zero dead band will also result in the system transitioning to the RECOVERY state.

RECOVERY

The normal purpose of the RECOVERY state is to manage the cable recovery after the glider releases at the top of the launch. The control mode is speed. A short, e.g. 1 second, audible signal shall be generated on entry into this state to signal the operator the winch is now under manual speed control. This again is done so that the operator does not need to take his eyes off the glider to determine the state of the winch system.

The control lever controls the cable speed with the Nominal Operating Position corresponding to an inherited speed. The inherited speed is the cable speed at the time of the transition into the state. If the entry was from the PROFILE state, this speed will be whatever the cable speed was when the abnormal transition occurred. If the cable had reached the target speed this will be around the suggested 1.5 V_s. If it is from the RAMP or CONSTANT state, the value is the cable speed at the time of the transition. If it was due to reaching the maximum cable speed value, typically around V_w – Headwind, this maximum value will be the value inherited. If it was due to the control lever being retarded to the Rest Position or the pressing of the ARM/RESET/ABORT pushbutton, the inherited speed will be the speed at the time of the induced transition. Further discussion of this recommendation is given shortly after discussion of control lever filtering provisions.

The control lever input into the control system will be filtered, suggested: first order linear with non-linear slew-rate limiting, to preclude high drum acceleration/decelerations, jerky operation, and the resulting excessive pressure transients in the hydraulic system. The negative slew rate limits are particularly important in this state to preclude slipping of the cable under rapid deceleration. The Appendix contains a description of a simple non-linear filtering function that realizes this behavior.

A subtle situation is the aborting of a launch from the PROFILE, RAMP, or CONSTANT states by retarding the control lever to the Rest Position with the glider still attached to the cable. What would prompt such an action by the operator is not clear. Nevertheless, this would transition the winch into the RECOVERY state. One might think the control lever being in the Rest Position would immediately brake the drum to zero speed and there would be a real possibility of the still connected glider flying into the opening parachute. However, the slew-rate limiting just described will limit how fast the drum decelerates giving the operator time to return the control lever to the nominal position. This position will now correspond to the speed at which the abort was ordered. Operating the winch in speed control with a glider connected is very dicey. Slow the cable too much and the glider potentially flies into the parachute. Increase the cable speed too much and the glider can overspeed. This condition is exacerbated by the inverted airspeed control behavior exhibited under cable speed control – pulling back increases airspeed. For this reason, the cable tension factor will be limited, e.g. 0.5, while in the RECOVERY state. The author solicits comments on scenarios where such aborts may be warranted and on the proposed behavior of the winch in such cases.

Deflections of the control lever aft of the Rest Position will result in higher deceleration rates than are provided in the normal range. This should only be used in abnormal situations. It is useful to consider some typical numbers. Assume the normal deceleration rate is limited to 1 G or about 10 m/s^2. If the cable speed was 40 m/s, it would take about 4 seconds for the drum to reach zero speed under this limit. Deflecting into the negative control lever range will allow the operator to command higher deceleration (braking) in an emergency with the attendant risk of cable slippage.

The system will count drum revolutions as the cable is initially extracted. This will allow the winch controller to estimate how much cable remains before the parachute and other end of cable paraphernalia would be pulled through the guide rollers. As the end of the cable approaches the winch, the controller will reduce the 100% cable speed value such that it will have stopped or be very low before the end of cable assembly reaches the winch.

When the cable is stopped, the engine remains at operational RPM but under no load. Remaining in this state for a short period may be desirable to cool down the engine. When this cool down is complete, the operator presses the Retrieve/Prep pushbutton which transitions the winch to the PREP state where the engine is taken to idle and the bypass value is opened to await the arrival of the retrieve vehicle. When the cable is attached to the retrieve vehicle, pressing the Retrieve/Prep pushbutton again transitions the system to the RETRIEVE state for cable extraction back to the launch point.

RETRIEVE

The RETRIEVE state is used when extracting the cable with the retrieve vehicle. It is identical to the PREP state except that a slight tension bias is applied to keep tension on the cable during the extraction and to prevent the drum from overrunning when the retrieve vehicle slows. The bypass value is activated and the engine is returned to idle on entering this state. The behavior is identical to the PREP state with a slight positive control lever deflection. Moving the control lever adjusts the command value relative to this offset.

Pushing the Retrieve/Prep pushbutton transitions the winch to the PREP state. Repeated activations of this pushbutton toggles the system between the PREP and RETRIEVE states.

This state may also be used as a precursor to the ARMED state. The slight bias may be useful to slightly tension the cable in preparation for the launch. The same transition conditions apply as for the PREP state. If this state is used as a precursor state to launching, consideration should be given to providing some tensioning capability in the ARMED state.

Software Programming Environment

The GUI functions are primarily user interface, database, parameter calculation, logging, and launch review aides. Wizards for easily entering the characteristics of gliders and pilots for entry to the database will be provided. As noted, it is expected to be implemented on a USB connected laptop or PDA. The GUI has no critical real-time responsibilities allowing the use of non-real-time operating systems. The most likely environment for it to be designed in is Windows and/or Windows Mobile. Linux would be another possibility but would probably exclude applicability to a PDA. There are numerous software packages available for notebooks and PDAs that will minimize the programming effort required to realize this functionality.

The winch controller will be implemented on an embedded microprocessor board. It will be programmed in a common language, most likely C. It may employ a commercial Real-Time Operating System (RTOS) but one may not be necessary as this is likely a single threaded application. If one is used, calls for system services will be minimized. The I/O interfaces to the physical plant will be partitioned to separate the automation functionality from the winch physical characteristics as much as possible. Using a common language, not using, or minimizing the use of, an RTOS, and partitioning the I/O interfaces will make this code portable so that it may be applied to winches with different microprocessors/RTOSs/physical plants with as little effort as possible.

Appendix

This appendix contains technical details for realizing certain functions too detailed for the body of the proposal but not contained in other references or for discussion of other implementation issues not relevant to the automation discussion. The intent was to document these ideas while they were still fresh. The primary value will be for detailed design phase.

Asymmetric Slew-Rate Limiting Input Filter

The proposal called for filtering the control lever inputs. In particular, limiting the peak accelerations/decelerations of the drum when in the RECOVERY state is important to prevent the cable slipping on the drum. This discussion will focus on the behavior in this speed controlled state but this filtering, with differing state dependent parameters, is employed during all the active states.

The commanded speed or tension is input by the operator via the control lever. Unfiltered, rapid motions by the operator could generate jerky behavior and induce high pressure transients in the hydrostatic transmission. The block diagram of Figure A1 illustrates an asymmetric slew-rate limiting input filter. It filters the control lever inputs being applied to the automatic feedback control loops. An analog depiction is employed even though the implementation would be digital in a real system.

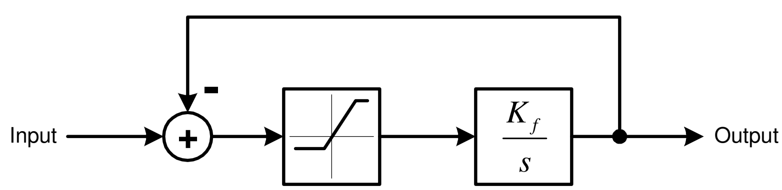

Figure A1. Asymmetric Slew-Rate Limiting Input Filter.

Without the saturation block, the input filter formed by proportional feedback around an integrator has a classic unity gain, first order response. The bandwidth of this linear filter would be K_f radians per second. Equivalently, the time constant of this filter would be $1/K_f$ seconds. Adding the saturation block limits the input values to the integrator to predetermined maximum positive and negative limits. When these limits are reached, the integrator then can only ramp linearly at a rate determined by these limits. The positive and negative limits can be different yielding an asymmetric slew-rate limiting behavior. When the rates of change do not induce this limiting action, the filtering follows the normal linear filtering trajectories.

The response of the filter to a square wave input, shown in Figure A2, illustrates these linear and non-linear behaviors. The time constant is 0.1 second and the slew-rate limits are 30 and -10. If the input units were meters per second, this would correspond to about 3 Gs positive and 1 G negative acceleration limits. The asymmetric slew-rate limiting behavior is clearly evident. The linear filtering effects are apparent in the exponential approach to the final values. The filter parameter values employed are only for illustration and appropriate values for the various states would be developed during the design phase and field trials.

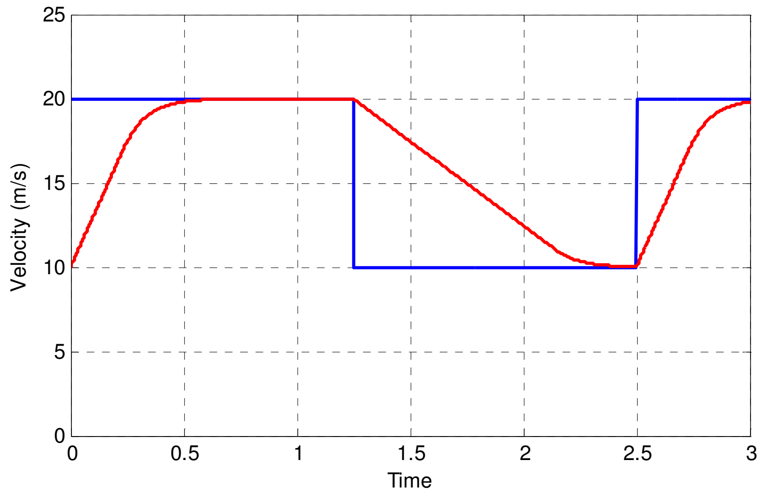

Figure A2. Square Wave Response of Slew-Rate Limiting Filter.

Upon entry into some states, the controlled parameter (tension, speed) may not match that associated with the control lever position. An example is an abort from the PROFILE state to the RECOVERY state. The cable speed may not correspond to the current control lever position. A smooth transition from the current condition to that commanded by the control lever may be realized by simply setting the value of the integrator to the current value on entry to the new state. The filter output will smoothly transition from this initial value to the value corresponding to the control lever as determined by the filter bandwidth and slew-rate limiting parameters.

Speed Controlled Loop for RECOVERY State

Earlier papers did not address the basic configuration of a speed controlled loop such as is required in the RECOVERY state.

Figure **A3** illustrates a simplified block diagram of a PI automatic control loop with slew-rate limiting input filtering. Some of the key elements that would be implemented digitally in the embedded controller are indicated.

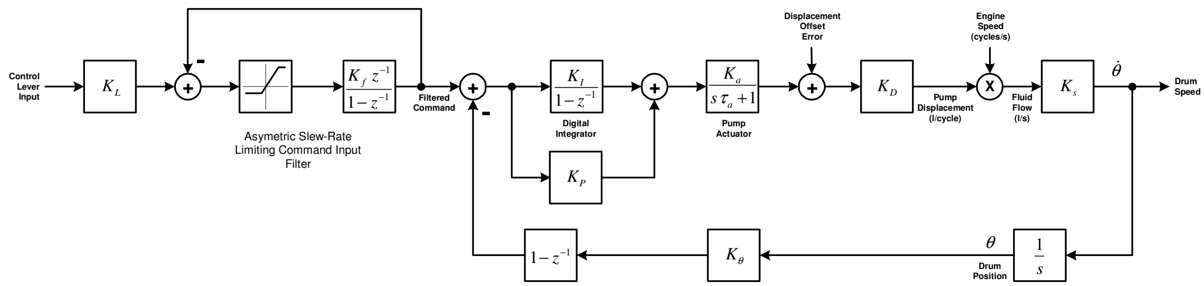

Figure A3. Conceptual Speed Controlled Feedback Loop.

The K_L block scales the control lever position for application to the loop. While shown as a constant gain, this block could be any memory-less non-linearity to shape the response to better suit the application. The transfer function would be state and launch specific, i.e. different states might use different shaped functions and the parameterization of these functions would be modified for each launch based on the glider, pilot, and launch characteristics desired.

The use of a position encoder and digital differentiator realizes the drum tachometer. Preliminary investigations suggest that at least 256 pulses per revolution should be employed. The "perfect" nature of digital differentiators and integrators is used in variations of this loop to prevent creep due to zeroing errors. Use of an analog tachometer would be subject to zero offset errors.

Braking Energy Conversion

While not fundamental to the automation discussion, a brief discussion of some issues with high braking action is now presented. Significant braking action is generally only applicable in the RECOVERY state. Braking the drum/motor system and any cable on the drum requires that the rotational energy of these be transferred or dissipated. Unless very heavy braking is employed (major aft deflections of the control lever), the pressure relief value will not activate so little energy will be dissipated in the hydrostatic transmission. So normally most of this rotational energy must be absorbed by the engine by a combination of an increase in the engine speed and/or dissipation in engine losses. When the engine speed begins to increase, the ECU should quickly reduce the throttle and pumping and friction losses will help dissipate the energy. But, if these losses are not sufficient, the engine speed will still increase. There is no fundamental problem with this speed increase up to the mechanical redline limits of the engine. The drum energy is simply being converted to rotational energy of the engine rotational mass. Analysis would need to be performed for each winch plant to determine if engine overspeed is an issue. Increasing the rotational inertia of the engine, such as by using a large flywheel, can mitigate this issue. Increasing the rotational inertia of the engine system has already been identified as beneficial in mitigating engine response issues under dynamic load changes.

References

These papers may be obtained from the Winch Design website or by contacting the author.

1. *Winch Dynamics*, George Moore, October 2005.

2. *Winch Dynamics Addendum*, George Moore, November 2005

3. *Non-Ideal Winch Behaviors and Compensation – Part 1*, George Moore, November, 2005.

4. *Flight on the Winch*, P.J. Goulthorpe, Sailplane and Gliding, June/July 1996, pp. 140-143.

5. *Preliminary Rotation Phase Investigation*, George Moore, February 2006.

6. *Constant Tension Performance Simulations and Sensitivities*, George Moore, March 2006.

7. *Non-Ideal Winch Behaviors and Compensation – Part 2*, George Moore, July 2006.

8. *Rotation Phase Investigation and Consolidated Launch Automation Scheme*, George Moore, October, 2006.

9. *Addendum to Rotation Phase Investigation and Consolidated Launch Automation Scheme*, George Moore, December, 2006.

Revision History

1.0

Numerous grammatical changes and clarifying modifications.

Original indicated PID controller was appropriate for tension control of hydraulic drive. Corrected to PI controller.

Reduced number of pushbuttons by consolidating and employing toggling action between states.

Disallowed transitions to the SAFE state from some states and required drum speed to be zero as a transition condition.

Retitled Emergency Stop to Emergency Off and embellished requirements for power off condition of critical elements (bypass value(s) and pump displacement actuator). Removed transitions in the state diagram for Emergency Off switch activation as electrical power is expected to be removed on its activation.

Modified RETREIVE state with tension bias for cable extraction and added RECOVERY state to handle cable recovery. Limited drum deceleration in RECOVERY state to preclude cable slipping. Negative range of the control lever to provides progressively higher braking in RECOVERY state. Added requirement for automatic speed reduction as the cable end nears the winch. Discussion of braking energy conversion and dissipation added.

Allowed transition to ARMED state from new RETRIEVE state. Identified alternate behavior for ARMED state and solicited comments.

Modified inherited speeds on abnormal entries into the RECOVERY state and limited maximum tension in this state. Solicited comments on these new recommendations.

Added option for warning lights to signify the winch is active with audible signal.

Added short audible signal on entry into the RECOVERY state and prior to leaving the SAFE state.

Added Appendix with slew-rate limiting filter and conceptual speed control loop descriptions.

1.1

Removed incorrect transition from the CONSTANT state to the SAFE state from state transition diagram.

Grammar changes and some additional clarifying additions.