The Design of a Dual-Use Pedal Control System for Use in a Roadable Aircraft

by

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SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IS PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2007

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Submitted to the Department of Mechanical Engineering
on May 11, 2007 in partial fulfillment of the
requirements for the Degree of Bachelor of Science in Engineering
as recommended by the Department of Mechanical Engineering

ABSTRACT

The goal of this project is the design of a control system that will make operation of the vehicle intuitive and efficient in both ground and air mode. Using relevant precedents and specific functional and regulatory requirements, this project covers the design of a dual-use pedal user interface control system for use in the Transition roadable aircraft concept in development by Terrafugia, Inc®, in Woburn, Massachusetts. The project includes construction of a mock-up as a proof of concept and for use in further development.

Thesis Supervisor: J. Kim Vandiver
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Table of Contents

1. Introduction

One of the challenges facing the successful launch of a roadable aircraft, is the design of a control system that will make the dual use vehicle safe and easy to operate in both modes. The General Aviation (GA) pilot community is growing, and many current airplane manufacturers are not adapting to the needs of the new private and sport pilots. The creation of a safe, efficient and affordable roadable aircraft would be a milestone for the future of General Aviation, and the control system is at the heart of this task. A roadable aircraft would not be feasible without an efficient, safe, and affordable dual-use control system.

The Transition roadable aircraft concept will be a solution to many of the problems now facing GA pilots. It will be able to travel to and from airports using drivable wheels with its wings folded up. The vehicle will convert to plane mode with the push of a button in a projected time of a few minutes (including checklists and walk-around), at which point it would be ready to fly. This will drastically decrease door-to-door travel time for flights, which is one of the major barriers to more widespread GA travel, according to a 2002 survey.[1]

The conceptualization and design of a pedal control layout that incorporates the systems, either separately, or in combination, needed by both the aircraft and the car, is the focus

[1] T. Downen, R.J. Hansman. "Identification and Analysis of Key Barriers to the Utility of General Aviation." Journal of Aircraft. 232-238, March-April 2003.

of this project. The final control system design will be a product of useful precedents, specific functional requirements and pilot feedback in an effort to make the Transition roadable concept a "must have" reality for GA pilots everywhere.

Figure 1 The Transition with its wings deployed, left, and with its wings folded up, right.

2. Background

2.1 A Brief History of Roadable Aircraft Patents and Control Systems

There is a long history of attempts at roadable aircraft design and construction. The more successful concepts, especially the ones that flew, tended to use simple control systems to operate the vehicle. There was some difference, however, in whether priority was given to the driving or flying controls. Some of the more successful designs and their control systems are outlined below.

Felix Longobardi filed the first patent for a multi-use vehicle in 1918 (U.S Patent # 1,286,679).[2] The vehicle would be able to drive, fly, and travel on water. It was never built.

In 1937, Waldo Waterman design-patented and built the Arrowbile (U.S. Design Patent #106,939).[3] The Arrowbile, seen in Figure 2, actually flew and five were built. The Arrowbile's contained mostly regulation automobile controls. The only flight control was a wheel/yoke that was suspended in front of the pilot from the cabin ceiling. Forward and back movements of the wheel controlled pitch, and turning the wheel produced coordinated turns. This means that the rudder and aileron control were coupled in the yoke, and the rudder could not be controlled separately.[4]

Figure 2 The Waterman Aerobile #6, an improved version of the Arrowbile.

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[2] Stiles, Palmer. Roadable Aircraft: From Wheels to Wings. Custom Creativity, Inc.: Melbourne, 1994.

[3] Ibid

[4] Cochrane, D. "Waterman Aerobile #6." Smithsonian National Air and Space Museum. 14 September, 2001. <http://www.nasm.si.edu/research/aero/aircraft/waterman.htm>

In 1946, Robert Fulton designed and built the Airphibian (U.S. Patent # 2,430,869).[5] It advertised a five-minute conversion time, and was certified by the CAA (would become the FAA). It had a detachable wing-tail-propeller section to be left behind at the airport. The same control system was used both for flying and driving. The control wheel was a steering wheel on the ground and a yoke in the air. The brake and clutch pedals converted to rudder pedals for use in the air. The pilot would have to disconnect and reconnect the control cables to the different control surfaces when transitioning from ground to air travel. Fulton devised a unique system of moveable pins to change the controls, and the engine would not start if all the control pins were not correctly placed.[6]

The most successful roadable aircraft concept to date has been Molt Taylor's Aerocar, patented in 1956 (U.S. Patent #2,767,939).[7] Unlike previous concepts with detachable wing sections that had to be left behind, the Aerocar, seen in Figure 3, could trailer its wings and propeller section behind it on the road. This allowed the vehicle to travel on the ground between airports rather than needing to takeoff from the same airport at which it landed. There were five prototypes built and flown, several of which are still airworthy.

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[5] Stiles, Palmer. Roadable Aircraft: From Wheels to Wings. Custom Creativity, Inc.: Melbourne, 1994.

[6] LeCompte, Tom. "Highways in the Sky." Hartford Advocate. 1999. New Mass. Media, Inc. 2006. <http://old.hartfordadvocate.com/articles/skycar.html>

[7] Stiles, Palmer. Roadable Aircraft: From Wheels to Wings. Custom Creativity, Inc.: Melbourne, 1994.

Figure 3 One of the remaining *Aerocars,* registered N102D.

The Aerocar uses a very straightforward pedal control system. It incorporates all five pedals necessary for the operation of the vehicle on the ground and in the air. Gas, brake and clutch pedals for the car are centered in front of the pilot in the foot well, and the two rudder pedals are situated on either side of the drive pedals.[8] Table 1 contains a summary of the control systems described above.

[8] Steeves, Richard. "Taylor Aerocar – N4994P." Airventure Museum. 2006. <http://www.airventuremuseum.org/collection/aircraft/Taylor%20Aerocar%20Design%20and%20Construction.asp>

Arrowbile			
PLANE MODE		CAR MODE	
Control Task	**Control System**	**Control Task**	**Control System**
Rudders	Yoke	Steering	Steering Wheel
Ailerons	Yoke	Acceleration	Accelerator Pedal
Elevator	Yoke	Braking	Brake Pedal
Ground Steering	Steering Wheel		
Ground Braking	Brake Pedal		
Airphibian			
PLANE MODE		CAR MODE	
Control Task	**Control System**	**Control Task**	**Control System**
Rudders	Gas/Clutch-Rudder Pedals	Steering	Control Wheel (yoke/steering wheel)
Ailerons	Control Wheel	Acceleration	Accelerator Pedal
Elevator	Control Wheel	Braking	Brake Pedal
Ground Steering	Control Wheel		
Ground Braking	Brake Pedal		
Aerocar			
PLANE MODE		CAR MODE	
Control Task	**Control System**	**Control Task**	**Control System**
Rudders	Rudder Pedals	Steering	Yoke/Steering Wheel
Ailerons	Yoke/Steering Wheel	Acceleration	Accelerator Pedal
Elevator	Yoke/Steering Wheel	Braking	Brake Pedal
Ground Steering	Toe Brakes		
Ground Braking	Toe Brakes		

Table 1 Summary of dual-use control systems previously implemented in roadable aircraft.

2.2 The Transition

The Transition, which is currently in development, is one of the most recent roadable aircraft concepts. The vehicle was first conceptualized by Carl Dietrich, the founder and CEO of Terrafugia, the company bringing the Transition to market.

The goal of the Transition is to minimize door-to-door travel time for sport and private pilots. The transition between plane and car mode requires no assembly or disassembly. A push of a button in the cockpit folds up the wings and makes the vehicle ready for road travel. The Transition will fit in any standard seven-foot garage, making it ideal for pilots who do not have a place to store an aircraft. The vehicle will also run on premium unleaded gasoline so the pilot will not need to purchase the more expensive AvGas (100 Low Lead), although it will run on it if necessary.

2.3 Regulations

The Transition will be required to meet standards for both road and air travel. For the road, the vehicle must adhere to the guidelines set forth by the National Highway Traffic Safety Administration (NHTSA), and the Federal Motor Vehicle Safety Standards (49 CFR part 571). In this area, exemptions are possible for small manufacturing operations (under 10,000 units per year), but initial design will work to avoid needing exemptions whenever possible. For the air, FAA's regulations for Light Sport Aircraft (LSA-ASTM) must be followed. This project will also consider applicable Federal Aviation Regulations (FAR part 23). Specific regulations that apply to the pedal control system being designed in this project will be followed. The specific regulation numbers that apply to this project can be found in Appendices A-C.

3. Procedure

The goal of this project is to create a design for a rudder/drive pedal control system to be used in the Transition roadable aircraft. The following procedure outlines the structure of the project.

(1) Control Requirements: The development of a list of control requirements for the vehicle, or what needs to be controlled.

(2) Control Allocation: The development of design concepts for user interface systems that satisfy all the control requirements.

(3) System Design: The design of a user control system, based on the chosen allocation scheme.

(4) Mock-Up: Creation of a mock-up to test the system design.

4. Results and Discussion

4.1 Control Requirements

The development of a list of control requirements for the vehicle needs to be established before any design work can be done. These are not design requirements for the system itself, but simply what on the vehicle needs to be controlled in order for it to function as intended.

Table 2 below lists what functions of the vehicle need to be controlled in both of the vehicles modes of operation. Note that throttle control for "Plane Mode" and gear shifting for "Car Mode" are not included because those functions have already been accounted for in the design of the other vehicle systems. A standard friction throttle is to be used for controlling the engine in flight and a continuously variable transmission (CVT) is to be used on the ground.

Plane Mode	**Car Mode**
Rudders (yaw control)	Steering
Ailerons (roll control)	Acceleration
Elevator (pitch control)	Braking
Ground Steering (taxiing, takeoff and landing)	
Ground Braking	

Table 2 List of the control requirements for the two different modes of vehicle operation.

4.2 Control Allocation

The previously enumerated functions now need a control system to operate them. Several control system concepts were developed to satisfy all of the requirements found in Table 2. Four different concepts were developed. For the sake of safety and adherence to motor vehicle regulations, every concept utilizes traditional driving controls, using a steering wheel to control the wheels, and gas and brake pedals to control acceleration and braking unless otherwise stated. Thus, the following concepts concentrate on the vehicle controls in "Plane Mode." Table 3 illustrates how each concept fulfils all the control requirements.

	Rudder Pedals	Flight Stick	Yoke/Steering Wheel	Hand Brake (on control stick)	Toe Brakes	Steering Wheel
Rudders	**1, 2, 3, 4**					
Ailerons		**1, 3, 4**	**2**			
Elevator		**1, 3, 4**	**2**			
Ground Steering	**1**		**2**		**4**	**3**
Ground Braking				**1, 2**	**3, 4**	

Table 3 Distribution of control requirements to different user-interface control devices for four control allocation concepts.

The concepts illustrated in Table 3 were subjected to a critical design review and the problems and benefits of each concept enumerated in order to down select a final scheme.

Concept 1:

Although having controls most similar to other small aircraft, steering the larger car-like wheels that the Transition will have using rudder pedals would require some sort of power assist steering, and such a system weighs too much to use in the vehicle. Also, the rudders would have additional inertia associated with the rudder pedals being joined with the wheels and steering wheel (used in "Car Mode"), and could induce unconventional control dynamics. Table 4 details to which control systems the requirements in Table 2 are assigned.

Plane Mode Control Task	Control System	**Car Mode** Control Task	Control System
Rudders	Rudder Pedals	Steering	Steering Wheel
Ailerons	Flight Stick	Acceleration	Accelerator Pedal
Elevator	Flight Stick	Braking	Brake Pedal
Ground Steering	Rudder Pedals		
Ground Braking	Hand Brake		

Table 4 Control allocation for Concept 1. Conflicting tasks are highlighted.

Concept 2:

A dual use yoke/wheel would require different amounts of turning (90° in each direction for the yoke, and 540° for the steering wheel) and both functions would need to be used for ground operations in "Plane Mode." This joint control also makes it impossible to taxi, land or takeoff in a crosswind, where aileron deflection might be necessary while maintaining a given direction with the wheels. Table 5 details to which control systems the requirements in Table 2 are assigned.

Plane Mode		Car Mode	
Control Task	Control System	Control Task	Control System
Rudders	Rudder Pedals	Steering	Yoke/Steering Wheel
Ailerons	Yoke/Steering Wheel	Acceleration	Accelerator Pedal
Elevator	Yoke/Steering Wheel	Braking	Brake Pedal
Ground Steering	Yoke/Steering Wheel		
Ground Braking	Hand Brake		

Table 5 Control allocation for Concept 2. Conflicting/problem producing tasks and systems are highlighted.

Concept 3:

Although the simplest in the sense that there are no coupling issues between control systems as in Concept 2, it would be impossible to cross-control the vehicle in a crosswind during taxiing, takeoff or landing because those situations would require the use of the steering wheel, throttle and stick at the same time, and the pilot would not be able to control all of these at once. Table 6 below details to which control systems the requirements in Table 2 are assigned.

Plane Mode		**Car Mode**	
Control Task	Control System	Control Task	Control System
Rudders	Rudder Pedals	Steering	Steering Wheel
Ailerons	Flight Stick	Acceleration	Accelerator Pedal
Elevator	Flight Stick	Braking	Brake Pedal
Ground Steering	Steering Wheel		
Ground Braking	Toe Brakes		

Table 6 Control allocation for Concept 3. Conflicting/problem producing tasks and systems are highlighted.

Concept 4:

Although braking to enact differential steering would require slightly castored wheels, which require slightly more force to turn with a steering wheel, the concept provides the best compromise between ease of use, simplicity, and effectiveness in any crosswind condition in which the vehicle would normally be able to fly. Table 7 below details to which control systems the requirements in Table 2 are assigned.

Plane Mode		**Car Mode**	
Control Task	Control System	Control Task	Control System
Rudders	Rudder Pedals	Steering	Steering Wheel
Ailerons	Flight Stick	Acceleration	Accelerator Pedal
Elevator	Flight Stick	Braking	Brake Pedal
Ground Steering	Toe Brakes		
Ground Braking	Toe Brakes		

Table 7 Control allocation for Concept 4.

Concept 4 was chosen as the best control allocation design, because of the lack of conflicts between systems.

4.3 System Design

The next step is to design a system based on the selected control allocation scheme of Concept 4 that could be successfully used to operate the vehicle. During this stage, in addition to any design requirements inherent in the control allocation concept, some functional requirements set forth by the vehicle's designers will need to be accounted for in the system concept.

These unique requirements are:

(1) Unimpeded movement of flight controls without the removal of any control systems. For example, the flight stick must clear the steering wheel during use without requiring the movement or detachment of the steering wheel.

(2) In car mode, the rudders must deflect inward to make the brake lights, situated on the outsides of the rudders, visible to cars behind the vehicle.

(3) Similarly, the elevator must deflect upward 60° in "Car Mode" to display the license plate, which is situated on the bottom of the control surface. This also allows the elevator to be used as a rear bumper that meets Federal regulations.

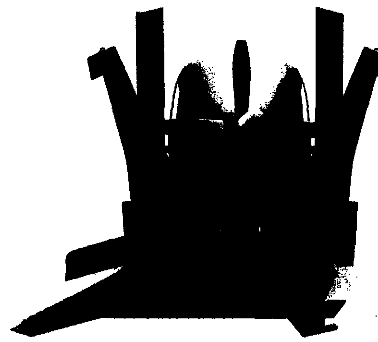

Figure 4 Rear view of the Transition, showing the brake lights and license plate revealed by the deflected rudders and elevator, respectively.

Based on the chosen control allocation scheme and the addition functional requirements enumerated above, a system was designed to fulfill the required functionality, preserve the "feel" of the control system in both vehicle modes and fit in the limited space of the cockpit.

The flight control system was designed to be stowed in "Car Mode" to allow the vehicle to be driven like a conventional car. For this reason, the rudder pedals fold up into the dashboard and the stick folds down under the driver's seat while in "Car Mode." Ideally, the transition from plane to car mode would require as little manual operation as possible. For this reason, the system lets the driver switch the control system from "Plane Mode" to "Car Mode" with a single action: simply folding the flight stick down beneath the driver's seat accomplishes everything needed to change modes.

System Overview:

- During flight, the rudder pedals operate in front of drive pedals and do not interfere
- After landing, pulling the stick back beyond normal operating region deflects the elevator up to reveal license plate and picks up “Cable Puller”
- Cable Puller pulls both rudders in, displaying brake lights, and pulls rudder pedals up into dashboard
- Stick folds below seat and locks in place while in Car Mode, holding rudders, elevator and rudder pedals in position

A schematic of the control layout can be seen in Figure 5.

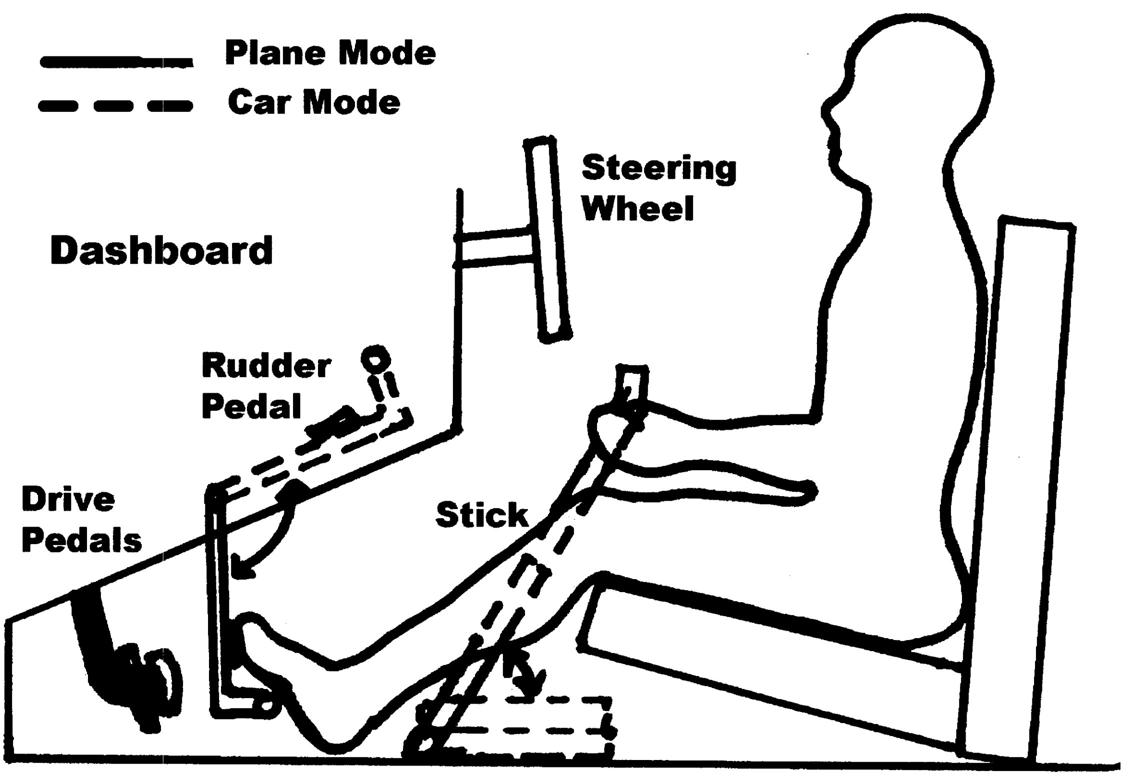

Figure 5 Schematic of the control system layout prescribed by Concept 4.

A schematic drawing of the system, seen in Figure 6, shows how folding the stick down beneath the seat pulls the rudders in, displaying the brake lights, pulls the rudder pedals up into the dashboard and provides for robust, continuous rudder control in “Plane Mode.”

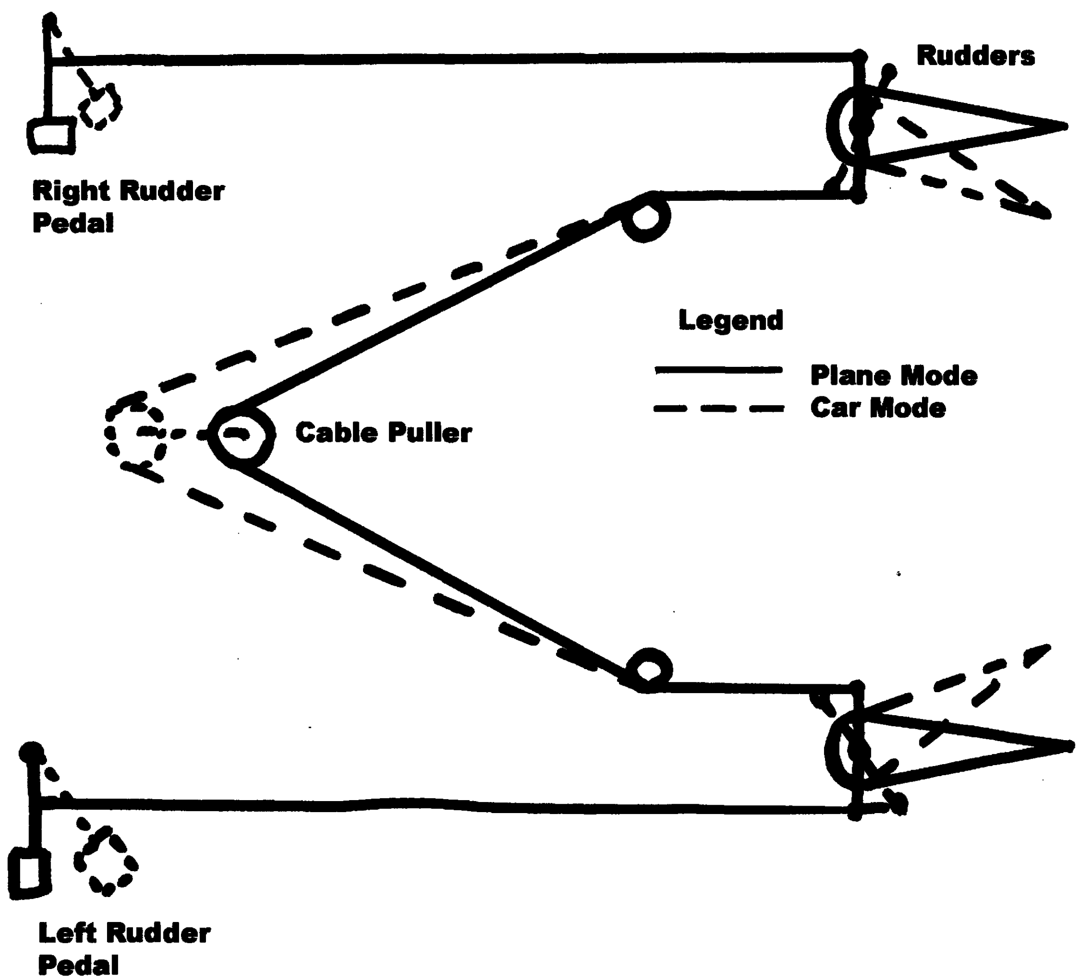

Figure 6 When the stick is folded beneath the seat, the cable puller pulls the rudder pedals up into the dashboard, and the rudders inward.

The cable puller, located in the center of the schematic, provides rigid rudder control “Plane Mode.” When transitioning to “Car Mode,” the stick is pulled beyond its normal operating range at which point it engages the cable puller, which in turn pulls the rudders in and the rudder pedals up. Schematic drawings of the stick's range and movement with the cable puller, the folding action of the rudder pedals and the deflection of the elevator can be seen in Figures 7, 8 and 9, respectively.

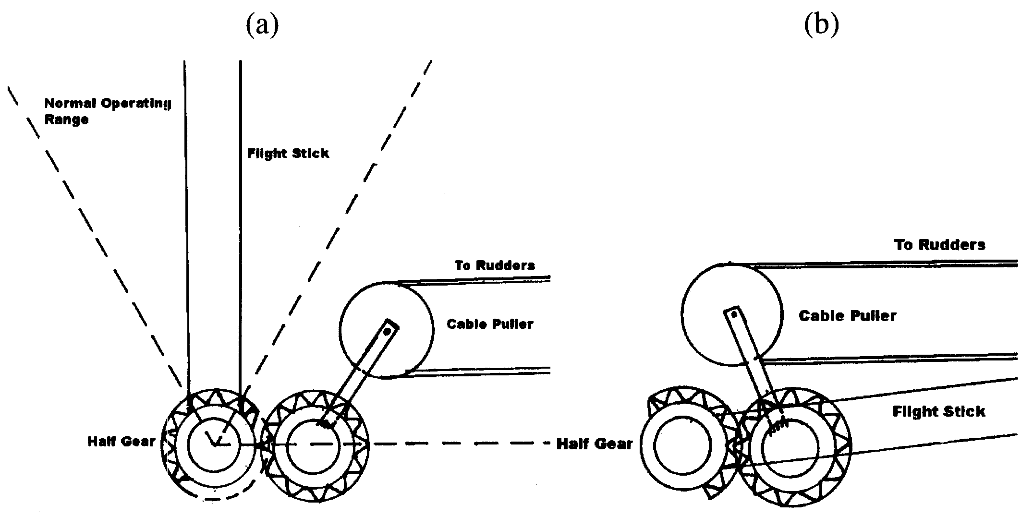

Figure 7 (a) The stick's movement within the normal operating range does not engage the cable puller. (b) When the stick is moved beyond the normal operating range and pushed to the floor, the cable puller is engaged and pulls the rudder control cables

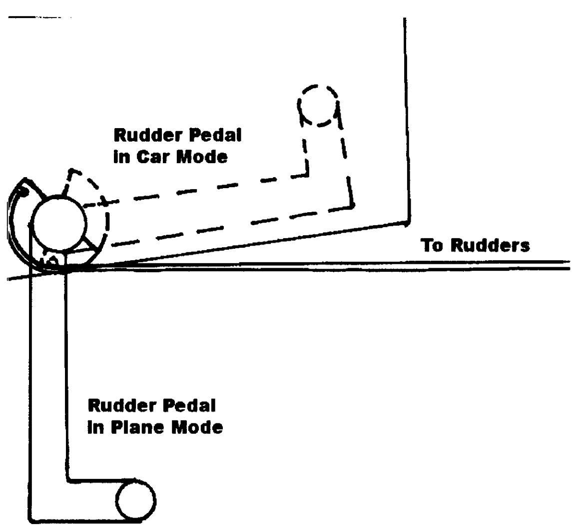

Figure 8 Rudder pedals in "Plane Mode" and in "Car Mode" stowed position after being manipulated by cable puller when stick is folded under seat

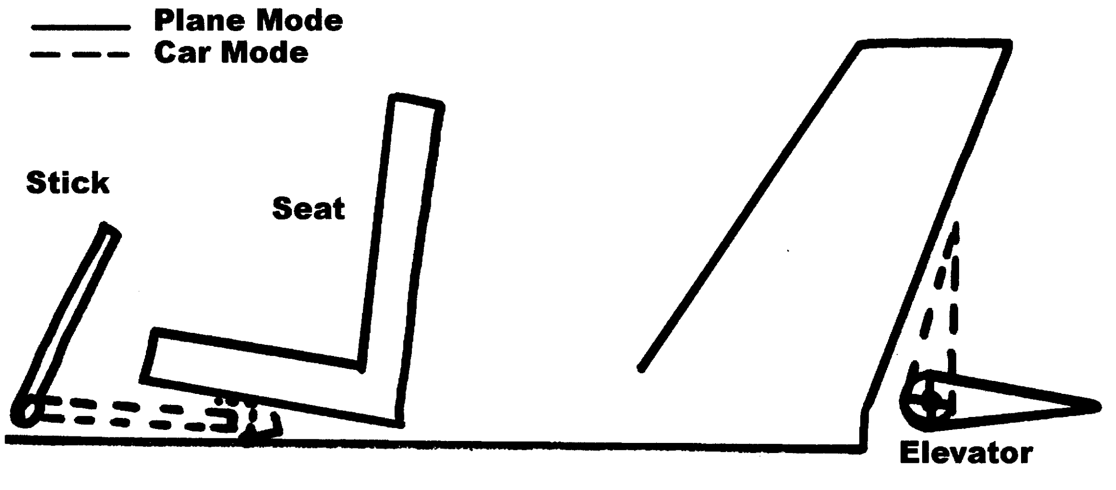

Figure 9 Schematic of the elevator deflection in transition from Plane to Car mode.

4.4 Mock-Up

The mock-up was constructed using inexpensive materials, primarily wood and PVC pipe. It effectively demonstrates that the conceptual system can work in the vehicle. The mock-up also includes the actual brake and gas pedal to be used in the vehicle prototype. Pictures of the mock-up can be seen in Figures 10, 11 and 12. The rudder pedals are attached on moveable mounts in order to correctly identify the appropriate mounting locations that leave enough room for their operation, as well as simulate possible movement of the pedals for drivers of different sizes and proportions. Most likely, the rudder pedals and drive pedals will be fixed at a location that, with a movable seat, can be operated easily by a male in the 95th percentile for anthropometric range in the United States and a female in the 5th percentile. The relevant anthropometric measurements are as stated by the Center for Disease Control (CDC) and the National Institute for Occupational Safety and Health (NIOSH).[9]

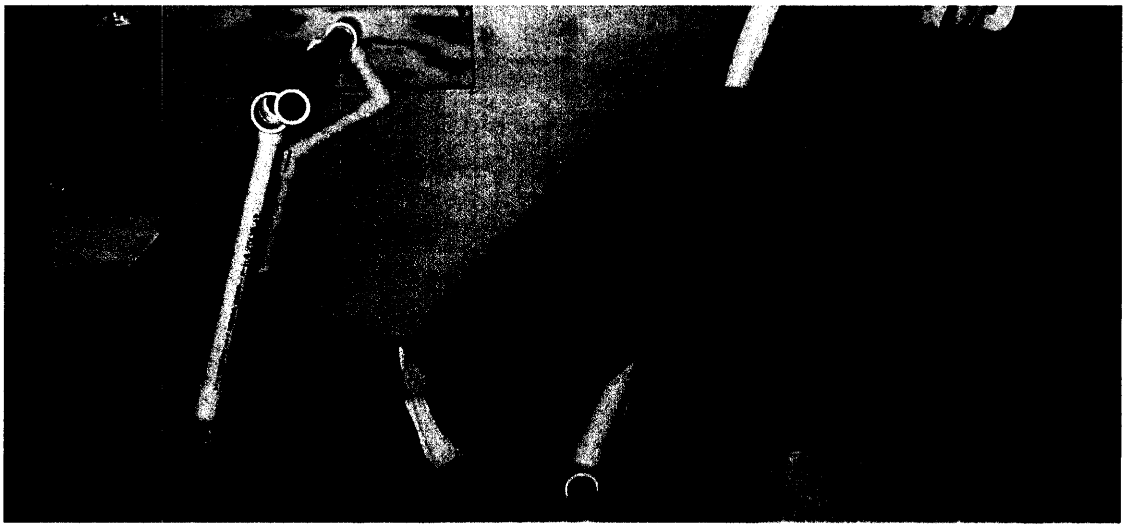

Figure 10 Use of rudder pedals and stick in "Plane Mode."

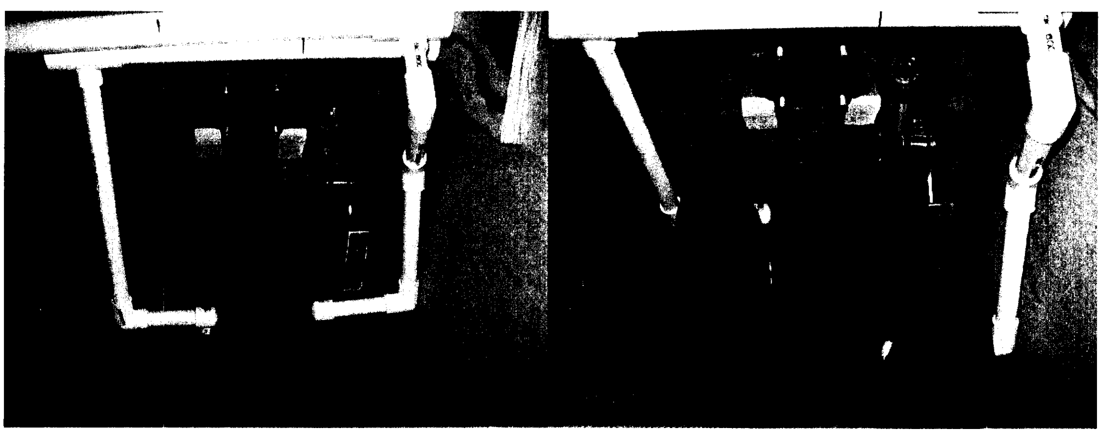

Figure 11 "Plane Mode"; Left: Rudder pedals down in neutral position; Right: rudder pedals in use.

[9] NIOSH. "Workstation Layout: Relevant Anthropometric Measures." CDC. <http://www.cdc.gov/niosh/pot_anth.html>

Figure 12 "Car Mode"; Left: Rudder pedals stowed; Right: Drive pedals in use.

The mock-up was successful in confirming the viability of the design, and some further observations were made:

- Initial estimates of cockpit space were inaccurate. The mock-up helped to solve some spatial problems and fix pedal spacing.
- The pedals will need to be shorter than designed to fold up into the dashboard.
- There is room for the pedals to fold back against the firewall, instead of into the dashboard, and this may be the focus of further design efforts as it will simplify the transition process.

5. Continuing Work

The mock up and design work up to this point will be used to develop final system and part designs for the vehicle prototype, whose construction is scheduled to begin in late summer or early fall. Once the prototype has been successfully flown, further alterations will be made and the system and parts will be designed for manufacturing. The timeline for this is unclear at this point, but production is estimated to begin in late 2009 to early 2010.

Appendix A: Applicable LSA–ASTM Regulations

4.5.3 Directional and Lateral Control
4.7 Ground control and stability
5.3.3-5.3.7 Control system regulations and load limits
5.3.10 Stops for gust loads

Appendix B: Applicable FAR Part 23 Regulations

23.143: General (Control system applied force limits, etc.)
23.147: Directional and lateral control
23.233: Directional stability and control
23.395: Control system loads
23.397: Limit control forces and torques
23.399: Dual control systems
23.415: Ground gust conditions
23.679: Control system locks
23.685: Control system details
23.687: Spring devices
23.689: Cable devices

Actual regulations can be found and searched at:
<http://www.airweb.faa.gov/Regulatory_and_Guidance_Library/rgFAR.nsf/MainFrame?OpenFrameSet>

Appendix C: Applicable Automotive Regulations – CFR Part 571: Federal Motor Vehicle Safety Standards

571.101: Controls and Displays
571.105: Hydraulic and Electric brake Systems
    S5.1.1-5.1.6, S6, S7
571.135: Light Vehicle Brake Systems