NASA-CR-192058

IN 37-CR
141673
P. 46

Georgia Institute of Technology
The George W. Woodruff School of Mechanical Engineering
Atlanta, Georgia

ME4182 Mechanical Engineering Design Project Report: Enabler Control Systems

June 11, 1992

(NASA-CR-192058) MECHANICAL ENGINEERING DESIGN PROJECT REPORT: ENABLER CONTROL SYSTEMS (Georgia Inst. of Tech.) 46 p

N93-18062

Unclas

G3/37 0141673

Presented to: Mr. James Brazell, Faculty Coordinator

Presented By: Controls Group

Christian Cullen, Group Leader
Dave Del Vecchio
Alan Scarborough
Andrew A. Havics

Table of Contents

Table of Contents (Continued)

1.0 Introduction and Problem Statement

The Controls Group was assigned the responsibility for designing the Enabler's control system. The requirement for the design was that the control system must provide a simple user interface to control the boom articulation joints, chassis articulation joints, and the wheel drive. The system required controlling hydraulic motors on the Enabler by implementing 8-bit microprocessor boards. The system requires controlling interface for motors from the wheels, articulation joints in both the boom and the chassis. In addition, feedback to evaluate positions and velocities must be interfaced to provide the operator with confirmation as well as control.

The internal combustion engine of the Enabler was designed to provide a constant pressure of 2400 psi. Hydraulic motors for the wheels were to be designed to provide a maximum speed of 5-7 MPH, ability to maneuver over a 1 meter object, cruise at approximately a constant speed, turn with reasonable accuracy and control, and permit forward and reverse movement.

This requires controlling the wheel motors in different modes for different applications. The wheels were to be designed to operate in three modes, drive (forward, reverse, speed control), lock, and off. During drive mode the wheels must have independent feedback to attain appropriate speeds. During turning operations, the wheels must be controlled so that the difference in rotational speeds between outer and inner wheels is consistent with the turn radius to prevent slipping and drag. The wheel control must also permit locking so that the torque necessary to prevent rolling while maneuvering over a 1 meter object is satisfied.

The hydraulic motors for the boom articulation joints were to be designed for on/off only with forward and reverse direction control. Each joint must be controllable by the Enabler operator by use of toggle switches. The boom articulation joints were to be designed to permit a rotational speed of 0.1 to 0.125 RPM. Position control was to provide set point to within 1-2 degrees of desired location as well as feedback of said position. In addition, the motors must be able to be locked upon reaching their set point position.

Chassis articulation joints were to be controlled individually by three motors per joint with ±180 degree motion per section. The chassis articulation joint hydraulic motors were to operate in three modes, on(CW/CCW control), off (free), and locked. The angle of rotation was to be measured and fed back to the operator. The angle feedback was also to be used to dictate and control the wheel speeds during turning sequences.

2.0 Design Objectives

The objective of this project was to provide a system to control the Enabler according the design specifications provided above. This included using a multi-input/multi-output MCU where closed-loop control was necessary. The control programs could then be downloaded into user RAM on the MCU and will send feedback to the control console and to the actuators.

The secondary portion of the objective was to create a control console interface that is simple and easy to use. This also requires that all components are accessible and able to be easily attained for repair purposes. All electrical systems must be DC and control circuitry must be designed to meet the voltage requirements of the sensors, actuators, and micro-controller units.

3.0 Control System

The control system was designed to interface with other components of the Enabler designed by the Articulation and Boom Joints Group, the Wheel and Wheel Drives Group, and the Articulation and Boom Structures Group.

3.1 General Background and Overview

The hydraulic system for all the motors is driven by a Vickers PVB-5 pump, which operates at a maximum 3600 psi and 10 GPM fluid flow. The pump will be operated at approximately a constant 2400 psi and provide a maximum 7.2 GPM, including efficiency losses, to the motors. Each motor will be controlled by its own HC11 board and appropriate servo-valve. Position and velocity feedback for the wheels and chassis articulation joints will be delivered directly to the HC11s for processing. The position feedback from the boom joints will be transmitted directly to the strawberry tree board. Control of the HC11s will be accomplished by a strawberry tree board which will in turn be controlled by the operator via the control computer. All changes for HC11 processing regarding moving over objects, turning, and speed control will be set by the operator on the control console and then relayed to the HC11s.

3.2 Wheel and Wheel Drive Control

3.2.1 Criteria

The wheels and wheel drive assembly were required to meet the following control criteria:

- provide the ability to independently control six wheels, thus their motors, for freewheeling, locked and normal operational situations

- provide flow control of hydraulic fluid at a range of 0-1.2 gallons per minute (GPM) to meet motor specifications

- hydraulic fluid flow control devices must be able to operate at 2400 ±100 psi

- control devices must be able to operate with an input voltage range of ±15VDC

- inlet/outlet ports should be in the range of 3/8" to 1/2" to adequately adapt to hose sizes required by motor

- provide ability to control the direction control of wheels and motors

- provide the ability to control velocity of wheels from 0-56 RPM

- provide ability to maneuver over a 1m object

- provide feedback to determine velocity and direction

- provide control devices to update wheel velocities

- provide control for vehicle turning

3.2.2 Motor Control

The motor selected by the Wheel and Wheel Drive group was a 1.5 HP Char-lynn, H+ Series, rated at 2.2 cubic inches/rev, with an operating pressure of 2400 psi and speed of 3250 RPM. This Char-lyn motor is a fixed displacement type requiring a maximum flow rate of 1.2 GPM to achieve a maximum speed of 2.92 MPH. Vickers SM-4-15 hydraulic servo-valves will be employed to control the hydraulic fluid flow rate to each of the wheel motors. A digital signal from each of the HC11 boards, in-line with the wheel motors, will be converted to Analog using the D/A module presented in Drawing D32-1. The analog signal will then be split into two identical signals. One of the signals will be relayed to the servo-valve through an invertor amp; the other signal will go directly to the valve. Velocity feedback will be achieved by the use of a Motorola digital encoder system connected to the wheel shaft. The digital signal produced by the encoder will be relayed through a chip then transported directly to the HC11 board.

3.2.3 Servo-Valve Control

The Servo-valve control system for each motor will contain the following components:

- Vickers SM-4-15 Servo-valve
- Vickers RS485 2-wire balanced serial line
- Vickers RS232 cable
- One switch in junction with an invertor op-amp
- Invertor op-amp
- Digital to Analog converter
- HC11 Board

The Vickers SM-4-15 servo-valve, presented in Drawing D32-2, is a flapper nozzle piloted servo-valve that provides low modulation, reversibility and fast response required for high performance. The specifications for the motor are presented below:

Table 1. Vickers SM-4-15 Servo-valve Specifications

Max pressure	3000 psi
Min pressure	200 psi
Max. Flow rating (@ 100psi drop and 5% non-linearity)	12 GPM
Internal Leakage (@3000 psi) Maximum	0.35 GPM
Operating Temperature	-40 to 121°C
Hysteresis (Around Null Point)	<2%
Pressure Null Shift (Nominal)	<2%/1000 psi
Temperature Null Shift (Nominal)	<2%/38°C
Flow Gain at Null	±50% nominal gain/1% rated current
Pressure Gain at Null	>25% supply press./1% rated current
Seals	Fluorocarbon
Weight	1.5 lbs (0.68kg)

The design criteria for operating conditions, 2400 psi and 0-1.2 GPM flow rate, were achieved by the use of this servo-valve. In addition, the valve operates well across a wide temperature range. The high end of this range(121°C/250°F) is more than adequate to prevent failure as a result of the friction buildup in the valve during operation. The hysteresis is also quite low (<2%). Although this is not necessary due to the feedback system incorporated in the control, it will prevent the shifting of the null point with respect to current input. The shifting of the null point could result in a maximum gain less than predicted, but more importantly, it could result in a flow reversal or oscillations about the null point. The flow gain at the null is also reasonable (±50%/1% rated current gain). This is important for operating around the null point, thus it is significant for locking the wheels and operating at low flow rates. Since the vehicle will be required to operate at very low flow rates, 0.38 GPM when climbing an obstacle, adequate control of this nature is imperative. At 0 VDC input, the valve will be locked permitting only leakage flow to ports A and B.

The weight of the servo-valves is 1.5 lbs, or approximately 14% of the motor weight. This slightly high but necessary for the control desired. The servo-valve itself encompasses approximately 4" x 2" x 3" of space. With the use of fluorocarbon seals, the effects of wear from friction and corrosion are expected to be relatively insignificant during its projected life.

The servo-valve consists of a double air-gap torque motor, a friction-free double nozzle pilot stage, and a sliding spool main stage. The valve position and output flow are approximately proportional to the magnitude of the electrical input voltage. The voltage change produces a current change approximately linearly proportional to the coil resistance. The current produces a definite position of the main-stage spool, however, this does not necessarily produce a fixed flow. The flow is a function of the square root of the difference between the supply pressure and the load pressure. A pressure drop of 60-100 psi at 12.5 GPM flow is expected across the servo-valve. This should be minimal compared to other factors, such as the demand from other motors. In addition, lower flow rates are expected, thus less pressure drop is expected. As substantial pressure drops are possible in the hydraulic system, the servo-valve was chosen such that its response time is much less than 1 sec. Because some fluctuation is expected to occur in the hydraulic pressure lines, due to the demands of independent control of 6 wheel motors and additional motors for the boom and chassis, the Vickers servo-valve is an excellent choice.

The average gain is approximately 1% rated flow to 1% rated input current with some variation at minimums and maximums (+20% to -10%) (see Graph 1). The amplitude ratio is approximately 1 at 10Hz, decreasing to .5 at 60 Hz. The phase lag is approximately 22 degrees at 10 Hz, increasing to 75 degrees at 60 Hz (see Graph 2). As the control frequency is expected to remain at <20 Hz, little if any effect will be observed in the servo-valve's performance. Typical robotic applications involve relatively low hydraulic resonance in the 3-5Hz range.

The Servo-valves will be rear mounted to the cylindrical chassis, approximately 1 ft. from the motor. The HC11 Boards will be located on the inside of the chassis tube and immediately adjacent will be the D/A converters and the invertor amplifiers. Because of the quality of the RS485 serial line, signals may be transmitted up to 500 feet without significant loss.

3.2.4 Speed and Direction Sensors

All six wheels will be monitored for speed. This will be accomplished by a Hewlitt-Packard optical encoder unit attached to each wheel axle (see Drawing D32-3). The digital information regarding speed will then be sent back to the HC11.

The Hewlitt-Packard (HP) optical encoder will be mounted on the wheel shaft adjacent the 5.725" diameter sprocket. One of the optical encoder leads will attached to a +5V DC source and the other to ground. The HP HEDS-6100-A06 Encoder disk (500CPR) consists of a disk with 500 slots along its periphery. The slots interrupts a two beams of infrared light generated by two light emitting diodes (LEDs). As the light passes through the slot, it is sensed by the photodiode. The disc rotates along with the shaft (and the wheel) , during which the photodiode receives the pulses of light in time. The number of pulses per unit of time is a measure of the rotational speed of the shaft. The signal produced will be sent from the HP HEDS-9000-A LED optical encoder module to one quad exclusive or gate (74LS86) chip. After processing the two signals into one it will then be sent to port A on the HC11. Thus 1000 pulses per revolution will be transmitted to the HC11. With a maximum 60 RPM wheel rotation, the frequency of the pulses will be 1000 Hz. The HC11 will process the signal and determine the speed using an internal timer mechanism characteristic of the HC11. This will be used to determine the shaft rotation speed and thus the vehicle speed in miles per hour (MPH).

3.2.5 Turn Ratio

When the vehicle turns, the outer radius wheels must rotate at a higher velocity than the inner radius wheels. In order to control the wheels during the a turning sequence, it was necessary to determine the ratio of these two radii. The ratio of the radii is approximately equivalent to the ratio of these speeds neglecting friction, deformation and minor geometrical changes of wheel base spacing.

This ratio was calculated for different turning angles using the following equation:

k_2 = outer radius/inner radius

$$k_2 = \frac{(0.5)*b*Tan(\Theta/2)}{[(0.5)*b*Tan(\Theta/2)] - [2*Tan(\Theta/2)]}$$

where b and Θ are represented in Drawing D32-4. The results of the calculations are presented in Table 2.

Table 2. Turn Radius Ratio

Θ(degrees)	k_2
0	1.000
2	1.019
4	1.037
6	1.057
8	1.076
10	1.097
12	1.117
14	1.138
16	1.160
18	1.182
20	1.205
22	1.228
24	1.252
26	1.277
28	1.302
30	1.328

The ratio between the two radii and thus the outer and inner wheel speeds was approximately linear at 0.1 RPM per RPM for every degree of the turn angle. Thus the wheel control during turning application was to be set at this ratio to prevent scuffing, tail end swing, and general mishandling and misdirection of the vehicle.

3.2.6 Feedback System and Valve Control

The digital signal from the Hewlitt-Packard optical encoder will be filtered through the 74LS86 chip and sent to the HC11. The signal will be processed by the HC11 and the appropriate output change will be directed to the D/A converter. After the D/A converter, the analog signal will be split into equal positive and negative signal voltages (the negative will be produced by the invertor amp). These signals will transmitted to the servo-valve. These signals will each be split again connecting in pairs to junctions A:C and to junctions B:D, representing the coil ends. A positive signal voltage to A:C will result in flow out of port B, thus forward motor motion. A positive signal to B:D will result in flow out of port A, thus reverse motor motion. The flow from the Vickers PVB5 pump will enter through port P, the pressurized port. Flow will return to the holding tank through port R, the return port. To operate the wheels and motor in reverse, a switch will be used in conjunction with an invertor op-amp to reverse polarity. This presented in Drawing D32-5. This switch will be triggered by the operator. A voltage of approximately zero will result in no flow, or a locked position. There will be some leakage, but this is expected to be minimal. The output voltage produced by using the D/A converter will be a maximum of ±12V DC. This will not achieve the maximum voltage range ±15V DC for the servo-valve. However, because the maximum flow rate for the servo-valve is 12.0 GPM (actual) and the amplitude ratio is approximately linear, the maximum flow rate for the servo-valve will be approximately 8 GPM. This well above the 1.2 GPM necessary.

3.3 Chassis Articulation Joint Control

3.3.1 Criteria

The articulation joints and joint drive assembly in the chassis were required to meet the following control criteria:

- provide ability to independently control the six joints, thus their motors, for locked and driven operations for turns, and freewheeling
- control devices must operate with an input range of ±15 VDC
- hydraulic fluid flow control devices must operate at 2400 ± 100psi
- inlet/outlet ports should be in the range of 3/8" to 1/2" to adequately adapt to hose sizes required by the motor
- provide constant rpm for any articulation of joints
- provide the ability to manually maneuver over a 1m object

- provide feedback to determine and maintain direction at each joint

- provide sensing devices to update joint position

- provide 1 degree of accuracy of position

- provide wheels with appropriate speed ratio

3.3.2 General

The two sets of articulation joints in the chassis were originally planned to be controlled in the following manner. The front set was to be articulated to the appropriate joint angles and the rear set of joints was to freewheel. The rear set would thus follow the front set in a 'snake-like' manner. This would have saved half the power needed to drive both sets. The current design does not allow this option since the worm gears cannot be disengaged, as required for freewheeling. The ability to lock the joints took precedence thus freewheeling was sacrificed. A proposal to be handled in the future to overcome this problem will be presented in Section 4.0 Future Development of this report.

The closed loop feedback is modeled as a steady state disturbance problem. Drawings D33-1 and D33-2 show the actual block diagram model of this setup. The chassis joints were to rotate at a fairly low RPM, around 0.1. For this reason it was necessary to model this as steady state. However, the motors per the current design are not controllable at these RPM ranges with the present gearing. Steady state is still used, however, even though rotation at present will occur at ~41 rpm, quite fast. The disturbance part of the model can be justified by the expected input. For example, the terrain which the Enabler will traverse is not expected to be flat, but slightly bumpy and rocky. These deviations off the plane of action act as tiny disturbances experienced in the wheels and chassis consisting of fluctuating loads. The form of the controller needed has not been designed, since no experimental setups were available. It is expected that a PD control will be implemented, as this controller has proven very robust.

3.3.3 Motor Control

The motor selected by the Articulation Joints Group was the Webster 22B hydraulic motor with operating pressure at 2500 psi and speed of 2500 rpm. The Webster 22B is a fixed displacement motor requiring 0.6 GPM to achieve the necessary torque to rotate the joint in a maximum load torque situation, climbing a 1m obstacle. Vickers SM-4-15 hydraulic servo valves will be employed to control the hydraulic flow to each of the articulation joints. The valve will control the direction of the flow and thus the direction of the rotation of the joints. The Articulation Joints Group specified a 83:1 gear ratio from the worm gear, which is driven at the rated speed of the motor, to the chassis itself. This equates to the joint rotating at 2500 RPM/83, or ~41 rpm. Detail of valve input needs are addressed in section 3.2.2. Speed control is limited mechanically for the chassis joints.

3.3.4 Servo-valve Control

The servo valve control system contains the following components:

- Vickers SM-4-15 Servo-valve
- Vickers RS485 2-wire balanced serial line
- Vickers RS232 cable
- One switch in junction with an invertor op-amp
- Invertor op-amp
- Digital to Analog converter
- HC11 Board
- Spectral 534-1-1-203 potentiometer

The Vickers SM-4-15 servo-valve is a flapper nozzle piloted servo-valve that provides low modulation, reversibility and fast response required for high performance. The specifications for the servo valve are presented in section 3.2.3.

The servo valves will be mounted inside the chassis approximately 6" from the motor. The HC11 boards will be located on the inside of the chassis and immediately adjacent will be the inverted amplifiers.

The valves will be receiving input from its own HC11, which in turn obtains input from three sources: User input from steering and climbing, and feedback from the potentiometer.

3.3.4.1 Steering

The desired angle for each joint is calculated from user input turning angle. The relationship between the turning angle and the angle of joint rotation is the following:

Turning angle = 2*arctan[tan(15)*cos(90-x/2)]

where x is the relative motion of the articulation joints. As shown in Drawing D33-3, one joint segment is called '1-2' and the other '2-3' ; x is the angle between these two joint segments. The angle of '1-2' and '2-3' relative to the fixed chassis is x/2. The joint angles above are calibrated to the appropriate voltage in the HC11 and the respective signal is sent to the correct valves via the op-amp invertor. Each joint set will receive the same signal from the user, i.e. (referring to the drawing D33-3) joint A1 and B1 are actuated identically, as is A2 and B2, as is A3 and B3. These details are given in section 3.5.3.2. The user desired angle turn converts to different inner and outer wheel speeds. These criteria are detailed in section 3.2.5.

3.3.4.2 Climbing

On climbs, the user will manipulate toggle switches to move the front and rear axles up or down. When these switches are thrown the vehicle will be expected to be in a straight fashion. When a command is chosen, the two appropriate motors will be rotated 180 degrees. This is detailed in Drawing D33-3. As shown in this drawing, when raising an axle the joints #'s 1 and 2 will be driven. When lowering an axle, joint #'s 2 and 3 will be driven. More detail is given in the climbing section 3.3.7.

3.3.5 Angular Position Sensors

All six joints will be monitored for position. This is accomplished by a Spectrol 534-1-1-203 (20K ohm resistance value), which has a maximum of 3600 degrees of mechanical turning. The potentiometer will be attached via a gear reducer to the exposed worm gear. The potentiometer will be mounted on the drive motor and receive input from the end of the worm gear. The turns of the worm gear will be transferred to the potentiometer by a gear ratio of 9:1. This ratio is based on 3500 degrees of the 3600 degree mechanical limit of the potentiometer, approximately one degree of precision in each joint and the 83:1 worm gear to chassis joint ratio. The appropriate gear train has yet to be designed (due to the last minute change in the chassis joint motor type). The design of this gear train must include attaching one gear to a 7/8 inch hex cut shaft in order to mount the potentiometer dial to the worm gear. The potentiometer itself must be anchored to the body.

The analog output from the potentiometer will be sent to the joint's HC11 where the position is updated. The rate of update will be crucial to the stability of the vehicle. This problem is addressed in Section 4.0 Future Development.

3.3.6 Feedback System

The analog signal from the potentiometer will be fed through an amplifier stage for 0 - 5 VDC input into the local HC11. The signal will processed by the HC11 and the appropriate output change will be directed to the D/A converter. The process from this point is precisely the same as stated in Section 3.2.6, Feedback System for Wheels.

3.3.7 Climbing Sequence

Maneuvering the vehicle over a 1m obstacle will be performed directly by the user. Two 3-position toggle switches are located on the control panel. Specifications for the toggle are found in section 3.4.4. Each toggle corresponds to front and rear joint sets. When either switch is in the 'up' position, the appropriate joints will rotate to raise the corresponding set of wheels, front or back; similarly for moving an axle down. To move an axle up or down only two joints need to be articulated equally while the third joint of this set remains locked. Solely from toggle input, the chosen joints will rotate 180 degrees and then lock. See Drawing D33-3 to view the specific joints necessary for rotation in each case. The user inputs will be sent to the ACMM, via channels 2 and 3 as shown in Drawing D35-2. These climbing toggles are discussed in more detail in Section 3.5. Digital Control.

To climb, the user must perform the following tasks once the vehicle is directly in front of the obstacle:

1) toggle front to up position
2) tilt boom backwards
3) toggle rear to up position
4) move vehicle forward until the front axle is on the obstacle
5) toggle rear axle to down position and front axle to home position(this will lift center axle to height of obstacle)
6) tilt boom forward to home position
7) move vehicle forward until the center axle wheels are on the obstacle
8) toggle the rear axle to home position
9) resume driving forward

3.4 Boom Control

3.4.1 Criteria

The boom control assembly was required to meet the following control criteria:

- provide the ability to independently control boom sections, thus their motors, to manipulate the boom within the movement envelope.

- provide flow control of hydraulic fluid at a range of 0-1.2 gallons per minute (GPM) to meet motor specifications

- hydraulic fluid flow control devices must be able to operate at 2400 ±100 psi

- control devices must be able to operate with an input voltage range of ±15VDC

- inlet/outlet ports should be in the range of 3/8" to 1/2" to adequately adapt to hose sizes required by motor

- provide ability to control the direction of rotation for each boom joint

- provide the ability to control velocity of .1 to .125 RPM

• provide feedback to determine position

• provide control to lock joints in place

3.4.2 General

The design of the lunar vehicle required a boom that could be used within a specified envelope around the vehicle. As a result, the boom consists of four moveable joints in which the movement and position are able to be controlled. The rotation and position of these joints are controlled by the operator. The operator relies on visual feedback and position feedback to accurately control the boom within the provided envelope (see Drawing D34-1). The movement is initiated manually and the position is transmitted from potentiometer to an HC11 and then to the strawberry tree board, which is located in the control console. This is displayed to the operator on the control panel, in degrees. The boom is then manually adjusted by the operator.

3.4.3 Motor Control

The type of motors that are located at each joint of the boom are to be self locking as specified by the Articulation Joints Group (Webster 22B hydraulic motor). Since these motors are self-locking, a servo-valve can be used to control the turning abilities of these joints. This servo-valve is the Vickers SM-4-15 as specified in Section 3.2.3. This servo valve will be used to control the direction in which the boom arm moves. The maximum rotational speed that was required (.1 to .125 RPM) was obtained through the gear train designed by the Articulation Joints Group. Therefore, speed control was limited mechanically for the boom joints.

3.4.4 Servo-valve Control

The servo-valve will be controlled by the operator, using Eaton toggle switches (flathand miniature-A121P32YZQ) mounted on the user control panel. Each toggle switch will have three positions, forward-off-reverse. The toggle switches will be applied to the ground portion of the circuit. This provides extra safety such that no current flows through these switches. When the toggle switch is in the forward position the valve will be powered for full fluid flow capacity. This is the same for the reverse position of the toggle switch.

A non-locking C&K Components, Inc. position switch (E215SD1CBE Moment-On-Moment) is used to control the turning radius of the joint. The switch is to be placed in line with the ground line of the valve and will provide a stop for the motor. This is accomplished by the switch being set to an open position by a tab located on the upper joint shell itself. The switch is to mounted on the non-moving lower part of the shell. Once the switch is set to its open position, the ground is terminated to the valve and the motor stops. One stopping switch will be used for both rotating directions of the motor. The stopping mechanism will not hinder the turning radius of the boom. Its main purpose is to protect the cables and hydraulic lines that run internally through the shell from unwanted twist or crimping.

3.4.5 Angular Position Sensors

The angular position control is designed on a feedback system that provides the operator with a number value, in degrees, that describes the position of the boom. A potentiometer was chosen to provide a measure of the position. The analog value in volts will transmitted to the Strawberry board. The Spectrol 534-1-1-203 (20 K ohm resistance value) potentiometer has a maximum of 3600 degrees of mechanical turning radius. It will be mounted on the drive motor itself and receive its input from the end of the worm gear. The end of the worm gear is exposed at the end of the self contained motor mechanism. The turns of the worm gear are to be transferred to the potentiometer via a gear mechanism. This gear mechanism must provide a reduction in the number of turns of the worm gear so the potentiometer does not exceed its mechanical limit. Therefore, the potentiometer must turn 360 degrees to an 40 degrees of rotation for the outer shell.

A one degree of precision for the boom position is also required. To obtain this criterion a gear ratio of 7:1 was required. The appropriate gear train must be designed. (due to last minute change in boom joint motor type). The design of this gear train must include attaching one gear to a 7/8 inch hex cut shaft in order to mount the potentiometer dial to the worm gear. The potentiometer itself must be anchored to the body.

The analog output of the potentiometer will be sent directly to the control module ACMM via CHAN5-8. The signals from the toggle switches are to be straight wired to the valve from the toggle switch.

Each joint will feed this output signal back to the strawberry tree board. This in turn provides a simple system to troubleshoot in cases of system malfunction. Extra length of cable will be also be provided. This will permit easy access and easy disconnection of cable connectors and hydraulic lines.

3.4.6 Feedback System

The initial position of the boom joint is generated by a 20K Ohm potentiometer. This analog value, in voltage, is then relayed to the strawberry tree board, which is located in the control console. The operator then visually determines the correct position of the boom. The operator further manipulates toggle switches to accurately maneuver the boom to the desired location in the provided movement envelope.

3.5 Digital Control

3.5.1 Overview

The Enabler Lunar Vehicle implements 16 hydraulic servo-motors in its wheel drive and articulation joint systems. Each must be controllable, by a single operator, with a sufficiently simple user interface to facilitate control over all systems. The following control systems were developed:

(1) Wheel Drive Speed Control

(2) Chassis Articulation Joint Steering Control

(3) Chassis Articulation Joint Climbing Control

(4) Boom Articulation Joint Control

(5) Basic Control Panel interfacing

The first two systems have been combined into one closed-loop system for the drive/steering mode. The second two systems are designed for use while in idle mode. The operator will need to control the articulation joints via toggle switches for the purposes of climbing obstacles, or positioning the boom. Finally, feedback will be available to the operator for all systems at all times via the control panel.

Control for all systems will be accomplished by a network of 8-bit microprocessor boards. Feedback, where required, will be delivered by electronic sensors. Hydraulic motor control will be actuated via 4-way servo-valves which regulate the hydraulic fluid flow driving each motor. Each of these systems, their configuration, and hardware components will be discussed in detail.

3.5.2 Microprocessor Control

Two different 8-bit microprocessors have been selected for the electronic network that will function as the "brain" of the onboard control systems.

The first is the Strawberry Tree ACM2-12-8 board designed for use with the Macintosh II microcomputer. Three of these cards will be implemented to interface the control panel with the remainder of the control network. In addition, the ACM2 boards will collect data from all potentiometer-based angle sensors located in the boom and chassis articulation joints.

The second is the Motorola MC68HC11EVB board. A total of 14 boards will be used to actuate all motors in the drive/steering and articulation joint control systems. Another primary function of these boards will be in communication of the set point values from the ACM2 cards in the control panel to the individual servo-motors in each system.

Both the Motorola and the Strawberry Tree boards' input and output signals in a range of 0 - 5 volts DC. As a result all interfaces between sensors/actuators and HC11s must include an amplifier stage to scale the operating voltage range of the device to the 0 - 5 V range of the HC11s. All voltages thus received by the board will be proportional to the voltages actually induced in the sensors.

The resolution provided by 8-bit micro controllers is limited, since the largest number a digital 8-bit port can accommodate is $FF or 255. This affords control at resolution of approximately 0.4% of the total range of the interfaced device. In the case of the angle sensing potentiometers this translates into an angular resolution of 1.44 degrees. Similarly, for a wheel with a max loaded speed of 60 RPM, this translates to a resolution of 0.235 RPM.

Currently an AC alternator will be attached to the IC engine. This will be connected to a separate power supply. The entire MCU network will be powered from a single DC power bus supplying the required voltages of +12V, -12V, +5V, and ground. This will be a Condor TAA-16AA DC power supply.

3.5.3 Speed/Steering Control System Hardware Setup

The Enabler Lunar Vehicle has been designed to travel over flat surfaces at speeds up to 3 mph. However, the controls system is equipped to handle speeds up to 7 mph. The set point speed will be determined by the position of a throttle lever. The center position of the throttle is an idle position. While idling, all 4-way servo valves are shut, bringing the six hydraulic wheel drive motors to a stop.

Forward displacement of the throttle opens the 2 valves for forward wheel rotation, and backward displacement opens the other 2 valves for backward wheel rotation. In reversing direction, the driver must first disengage all hydraulic wheel drive motors by setting the throttle to the idle position, allowing the vehicle to come to a stop, only then can the driver safely engage the drive motors in the reverse direction. This type of control is commonly used in most power boats and will afford the operator a proven, simple-to-use interface.

This throttle lever will produce a specific analog signal between 0 and +5 V DC which will be sent to two ACM cards designated ACML and ACMR in Drawing D35-1. A full 5 V in either direction corresponds to full speed, and 0 V corresponds to the idle position. This set point is input to both ACML and ACMR via analog input CHAN1 on each card's T51 interface panel. In this way, the set point (between $00 and $FF) is made proportional to the desired velocity. Card ACML interfaces with the left wheel drive controllers, while card ACMR interfaces with the right.

3.5.3.1 Cruise Control

When the angular deflections of the articulation joints are zero (i.e. when the joints are set for straight-line motion), the user determined set point value is unchanged. The set point is sent to the corresponding HC11 mounted at the center right/left wheel. This signal is sent from each ACM card's 8-bit digital I/O port to the fixed input port A on the middle wheel HC11 boards designated HC11ML and HC11MR. In turn these cards send a digital set point signal via fixed output port B to fixed input port E of the front wheel drive controllers HC11FL and HC11FR. Likewise, the middle right and left HC11s send the set point to the back wheel drives from programmable port C (configured to output), to port E of the corresponding boards HC11BL and HC11BR. All connections are shown in Drawing D35-1.

These set point values are continually updated during operation so that the driver may change speeds with minimal lag. Updates will occur once every 0.5 seconds, to avoid error propagation in the closed-loop control of each individual wheel. Such error propagation can occur when doing high frequency updates or data acquisition.

During operation the wheels' shaft speeds are continuously read by optical sensors. The Hewlett-Packard HEDS 9000A encoder module was chosen. The feedback circuit is detailed in D32-3. This circuit uses the encoder module to generate 1000 pulses per revolution of the wheel. These pulses are fed to the SN74LS86 Schmitt Trigger chip which generates a pulse train to feed back to the local HC11 via fixed-input port A. One of the key features of the HC11 MCU is its timer system, accessible through port A. Wheel speed feedback is fed to the timer, where the input capture function of the timer is used for speed measurement. The max desired wheel speed and the corresponding max hydraulic motor flow rate must both be set proportional to $FF or 5 VDC in the amplifier stage of the sensor/actuator interfaces, so that the feedback to the HC11s will properly compare with the set point signal fed to the actuating valves. The wheel speed feedback value is then compared to the set point desired speed and the signal to the actuating 4-way valve is modified by the resident motor control program in the user RAM in the MCU. This modified output to the servo-valve results in the flow rate to the hydraulic drive motor being increased or decreased as needed to maintain the desired speed.

The component selected to actuate hydraulic motor control was the Vickers SM-4-15 servo-valve. A built in switch on the throttle will set the polarities of the signals sent to the servo-valve interface circuit, for direction control. This circuit is detailed in D32-5, and uses 2 inverting amplifiers with unity gain for the control of each motor. The direction of the flow to the drive motors is thus determined by the polarities of the signals sent from the HC11/HEDS9000A setup to the servo-valves' motor coils.

3.5.3.2 Steering Control

When steering, the operator manipulates the chassis joints via a control lever. The center position of this lever is the straight-line, or 0 degree turn position. Positioning the lever to the right results in the articulation joints rotating to produce a right turn with the turning radius corresponding to the lever position, within a range of 0 to 30 degrees. Left turns are accomplished in the same manner by positioning the lever to the left.

The control panel's steering lever will produce an analog signal between 0 and 5V DC which will be sent to all three ACM cards via CHAN4 of the board's T51 interface panel as shown in Drawing D35-2. A program on ACMM will calculate the relative angular positions of the articulation joint segments for the user set turn angle. These values will be sent to the HC11 network also shown in Drawing D35-2. Four HC11s must be implemented to control each group of three articulation joint motors due to hardware I/O port limitations.

Each HC11 board will read the potentiometer angle position for its respective motor and compare it with the set point value. When these values are matched, the motor comes to a stop. When not matched, the motor adjusts the articulation joint to the desired position. The HC11 will output a signal via port C to the servo valve interface circuit detailed in Drawing D32-5. The polarity of this output signal controls the direction of the hydraulic motor, and is determined by the position of the steering control lever (CW or CCW).

Two of the front articulation joint angle sensors will send feedback to cards ACML and ACMR to provide them with the necessary data to calculate the adjusted, respective left and right wheel speed set points. The inner and outer wheel speeds are coordinated in this manner (See Sect. 3.2.5 Turn Ratio).

3.5.4 Articulation Joint Climbing Sequence

Initially, the chassis must be in its "home" position, all joints are straight. Next the climbing sequence can proceed as outlined in Section 3.3.7. TOGF will control the front joint set, while TOGB controls the rear. TOGF and TOGB in their zero positions send no signal output. TOGF will input to CHAN1 of ACMM and TOGB will input to CHAN2 of ACMM. Once a toggle is engaged ACMM will send the set point articulation joint positions to JF1, for the front set, and to JB1 for the back set. At this point the angular position control proceeds as outlined in the previous section.(See Sect 3.3.7).

3.5.5 Boom Articulation Joint Control

The boom articulation joints' angular positions will be controlled directly from 4 toggle switches located on the control panel. When toggled on, the corresponding joint will rotate until toggled off. The toggle switch will have three positions, off, CW, and CCW. When toggled on, the position of the toggle switch will set the polarity of the 5V signal sent to the corresponding servo-valve interface circuit as shown in Drawing D32-5.

The feedback for the boom articulation will be provided by the same potentiometer angle sensors as the chassis articulation joints. These four signals will be transmitted to channels 5 through 8 of ACMM, which will in turn update a digital display on the control console as shown in Drawing D35-2.

3.6 <u>Cables, Connectors and Hydraulic Lines</u>

The cable connectors are Amphenol circular (round military) connectors (97-3107-B-28-15-P-Y and 97-3107-B-28-15-S-Y). These connectors will provide good strength ease of use (connect/disconnect). This type of connector has guided connection, That is , the connectors are designed so that the correct pins are mated together when the connector is assembled. Also, the connectors are locked together and therefore provide a strong slipless connection. Furthermore, the connectors have a strain relief mechanism provided by the manufacturer. This protects the wires from being pulled out of their respective pin positions or from being twisted and pulled apart. These connectors have 35 pins which will provide room for future expansion.

The cable used for transmission of data from the host computer to the Enabler and the HC11s will be approximately 120 ft. It will consist Beldon 9V28064 cable, and RS232 cable for ground connection of the toggle switches. The cable from the potentiometers will consist of a shielded cable. The cable from the HC11s to the servo-valves will be Vickers RS485. The remaining cable will consist of Vickers RS232 (MCU to MAC) and standard 16 gauge insulated copper wire.

Based on the pump and motor characteristics, the hydraulic hose must be rated to SAE100R2 standards. Aeroquip Hi-Pac 3/8" nominal hydraulic hose, which costs less than standard SAE100R2 hose, will be used. This hose bends tighter by 25-33% and weighs 34-49% less than standard hose. It is operable at temperatures up to 93°C(200°F) and pressures up to 5,000 psi (4,000 psi for 3/8"). All connections will be Aeroquip fittings, that are compatible with the servo-valves and the motors. Hose connections will be quick disconnect snap fittings, usable while operating at high pressure.

4.0 Future Developments

The current design of the articulation joint motors does not permit a freewheeling option. In the future, a mechanism can be designed to disengage the worm gear from the drive gear, which rotates the chassis. With the worm gear disengaged, the chassis joints are allowed to freewheel.

As is the case with all feedback systems, instability is a factor which cannot be disregarded. In the ENABLER, specifically in its wheels and chassis, the rate of updating the set points must be determined to maintain stability. These calculations to determine these values can be done accurately once an experimental setup has been built. By trying smaller and smaller update times, one will be able to observe which time provides the best performance.

Also, with an experimental setup, one can calibrate the valves to meet higher performance specifications. The exact input/output relationship, the current/flow proportion can be determined in the manner presented below.

Once a model has been constructed, the servo valve should be cycled through its input range while recording a continuous plot of the output flow. This will graphically present the input/output relationship. This plot will exhibit three main regions: 1) null region with low current 2)the normal operating range and 3) flow saturation near the rated currents. From here, scaling of the usable input current to the output flow can be easily performed. The normal operating region should be close to linear, but any outlying areas can be evaluated to determine potential problems.

Respectfully Submitted by:

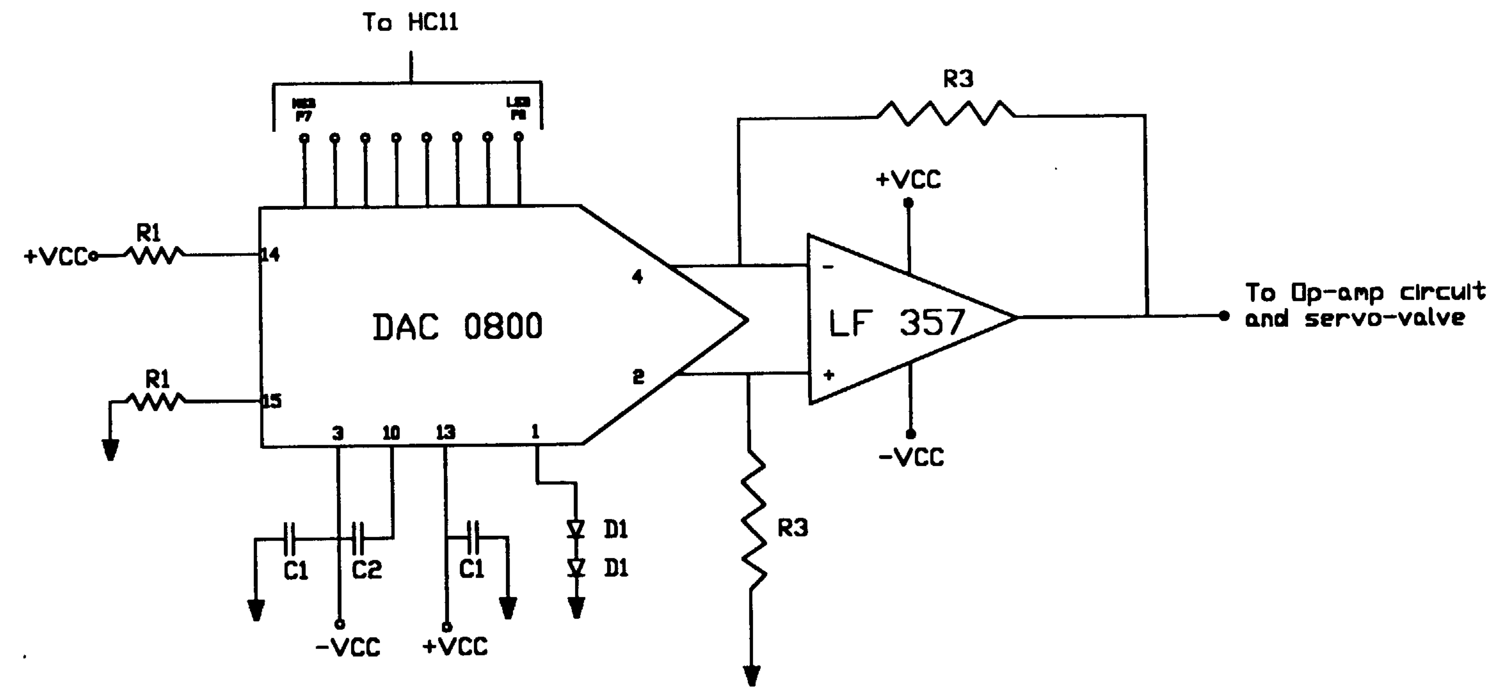
Christian Cullen

Dave Del Vecchio

Alan Scarborough

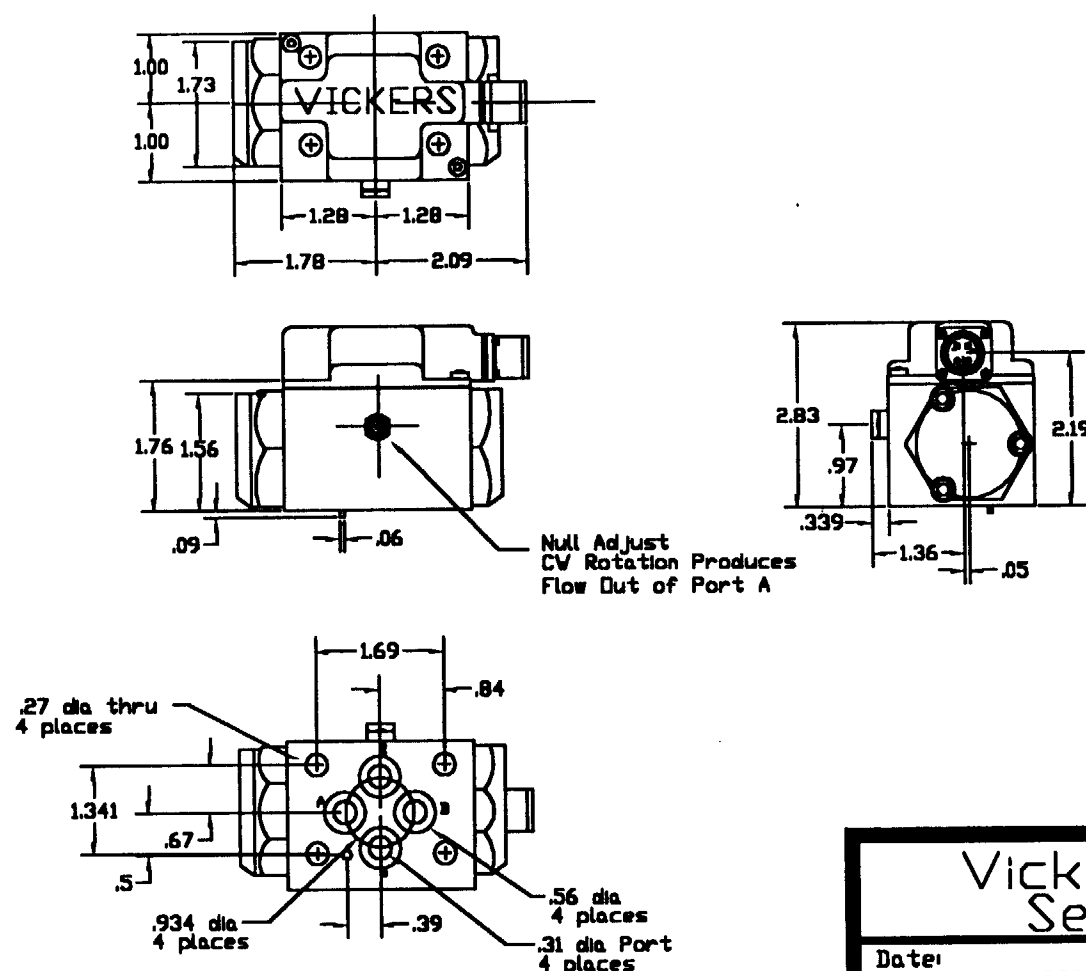
Andrew A. Havics

Appendix A
Drawings



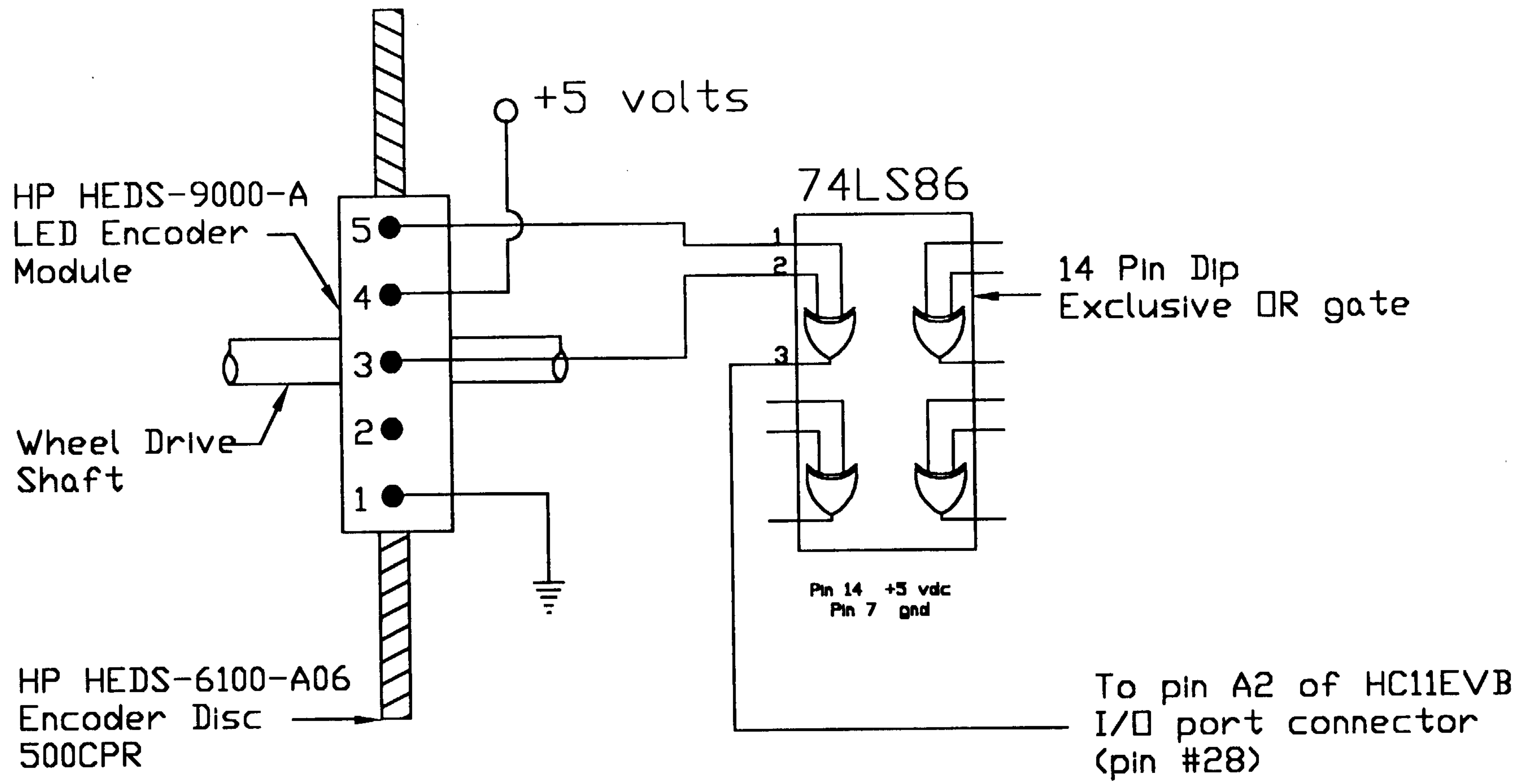
Notes: R1 = 5K ohms
R3 = 5K ohms
C1 = .1 micofarads
C2 = .01 microfarads

D/A Converter Diagram		
Date: June 10,1992	Group Name & Number	
Class: ME 4182	Controls Group Group #4	
Professor: Brazell	Group leader initials	Support
Drawing number: D32-1	Support	Support



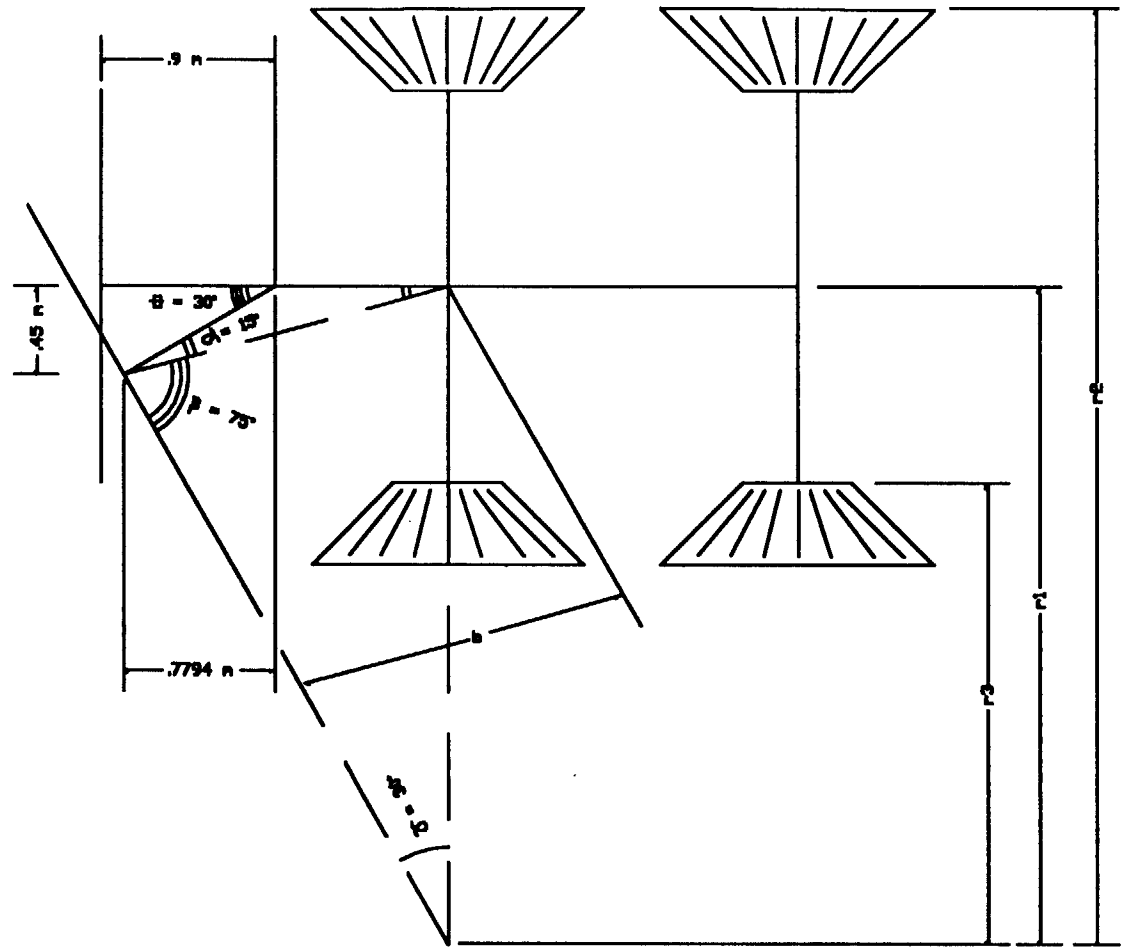
Note: All dimensions are in inches

Vickers SM-4-15 Servo-valve	
Date: June 10,1992	Group Name & Number: Controls Group Group #4
Class: ME 4182	
Professor: Brazell	Group leader initials / Support
Drawing number: D32-2	Support / Support



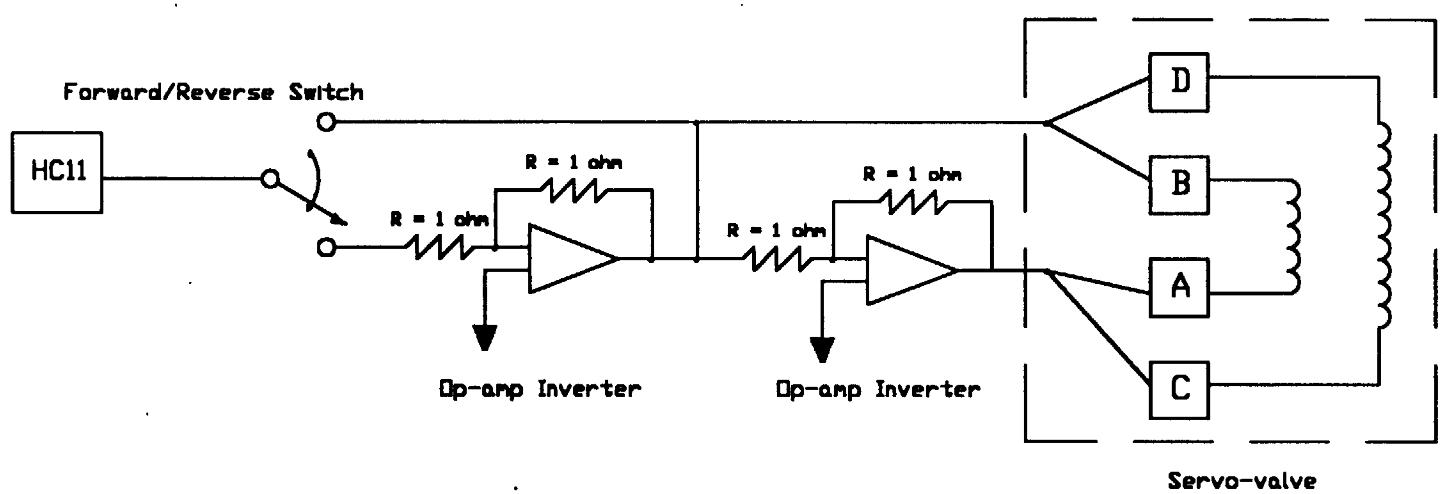
Wheel Drive Feedback Circuit Diagram

Date: June 7,1992	Group Name & Number: Controls Group Group #4
Class: ME 4182	
Professor: Brazell	Group leader initials / Support
Drawing number: D32-3	Support / Support



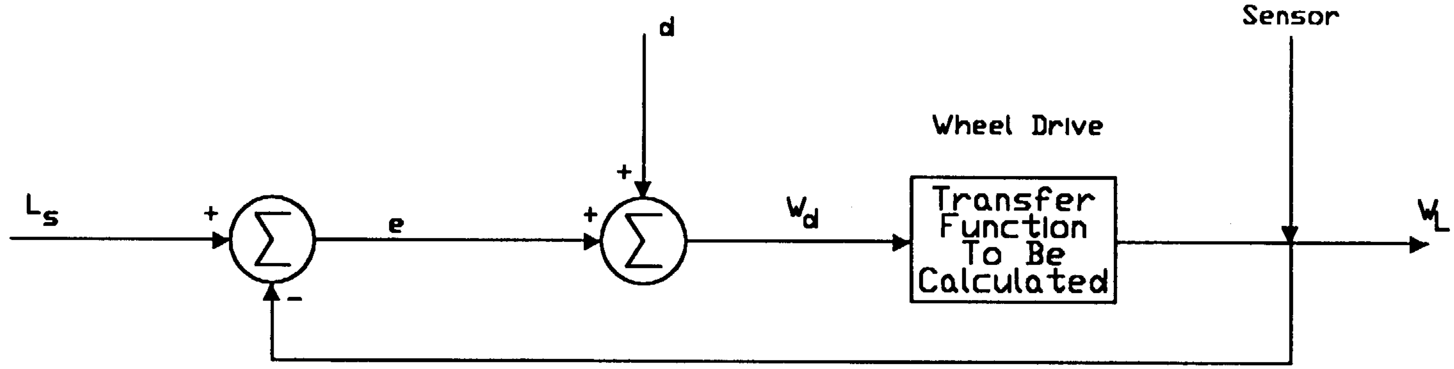
Turn Radius Ratio Diagram

Date: June 10,1992	Group Name & Number: Controls Group Group #4
Class: ME 4182	
Professor: Brazell	Group leader initials: / Support:
Drawing number: D32-4	Support: / Support:

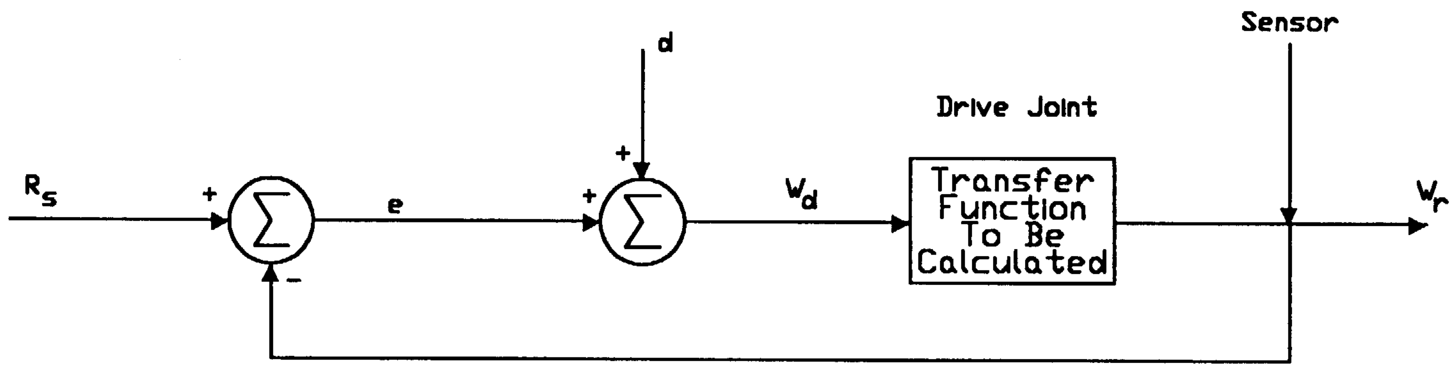


Op-amp Inverter & Switch Diagram

Date: June 10,1992	Group Name & Number: Controls Group Group #4	
Class: ME 4182		
Professor: Brazell	Group leader initials	Support
Drawing number: D32-5	Support	Support

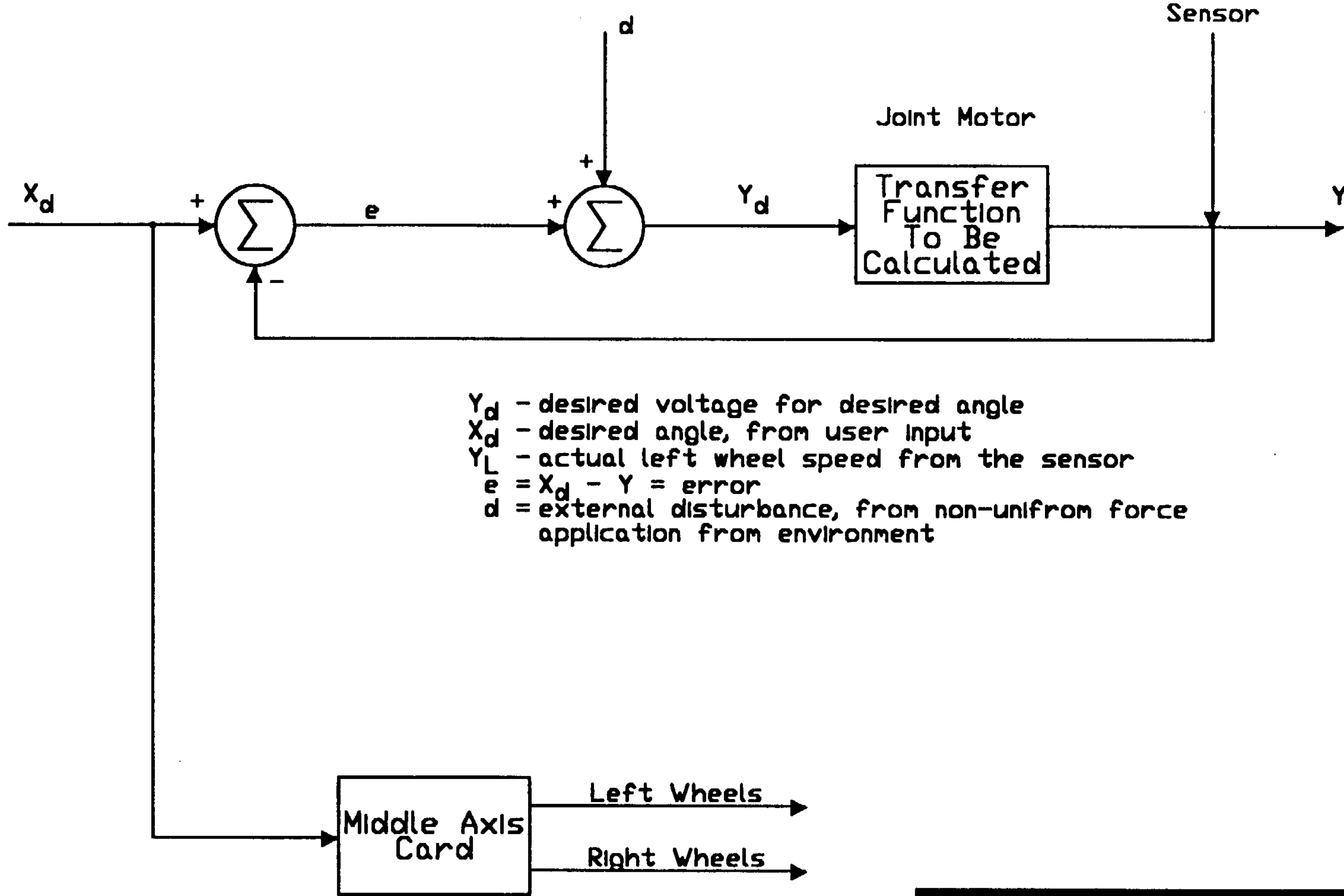


W_d -desire voltage for desired speed
L_s - desired left wheel speed, from desired angle
W_L -actual left wheel speed from the sensor
$e = L_s - W_L$ = error



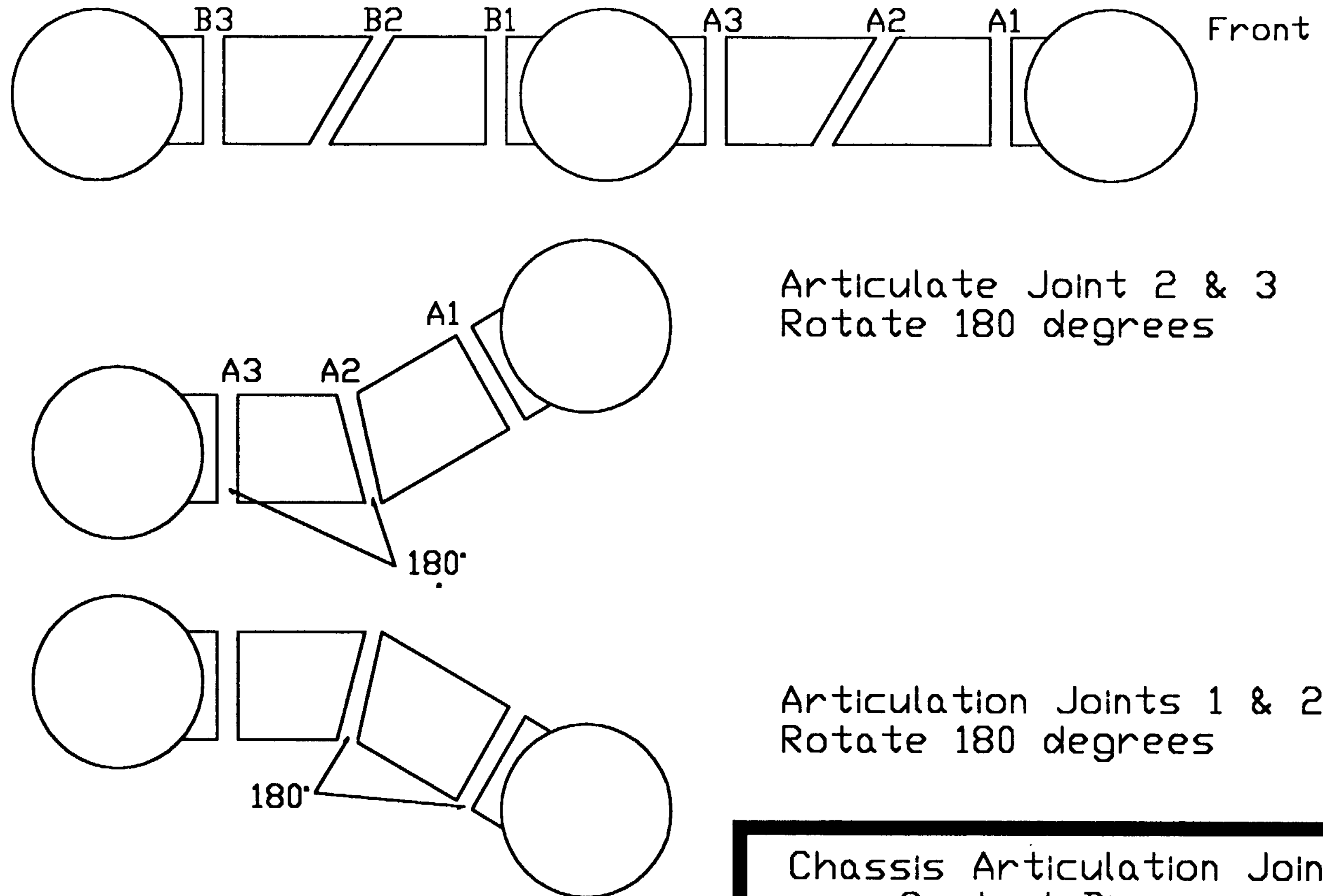
W_d -desired voltage for desired speed
R_s - desired right wheel speed, from desired angle
W_r -actual right wheel speed, from the sensor
$e = R_s - W_r$ = error

Vehicle Control Wheel Motor Control Circuit		
Date: May 20,1992	Group Name & Number: Controls Group Group #4	
Class: ME 4182		
Professor: Brazell		
Drawing number: D33-1	Group leader initials	Support
	Support	Support



Y_d - desired voltage for desired angle
X_d - desired angle, from user input
Y_L - actual left wheel speed from the sensor
$e = X_d - Y$ = error
d = external disturbance, from non-unifrom force application from environment

Vehicle Control Steering Control Circuit	
Date: May 20,1992	Group Name & Number: Controls Group Group #4
Class: ME 4182	
Professor: Brazell	Group leader initials / Support
Drawing number: D33-2	Support / Support

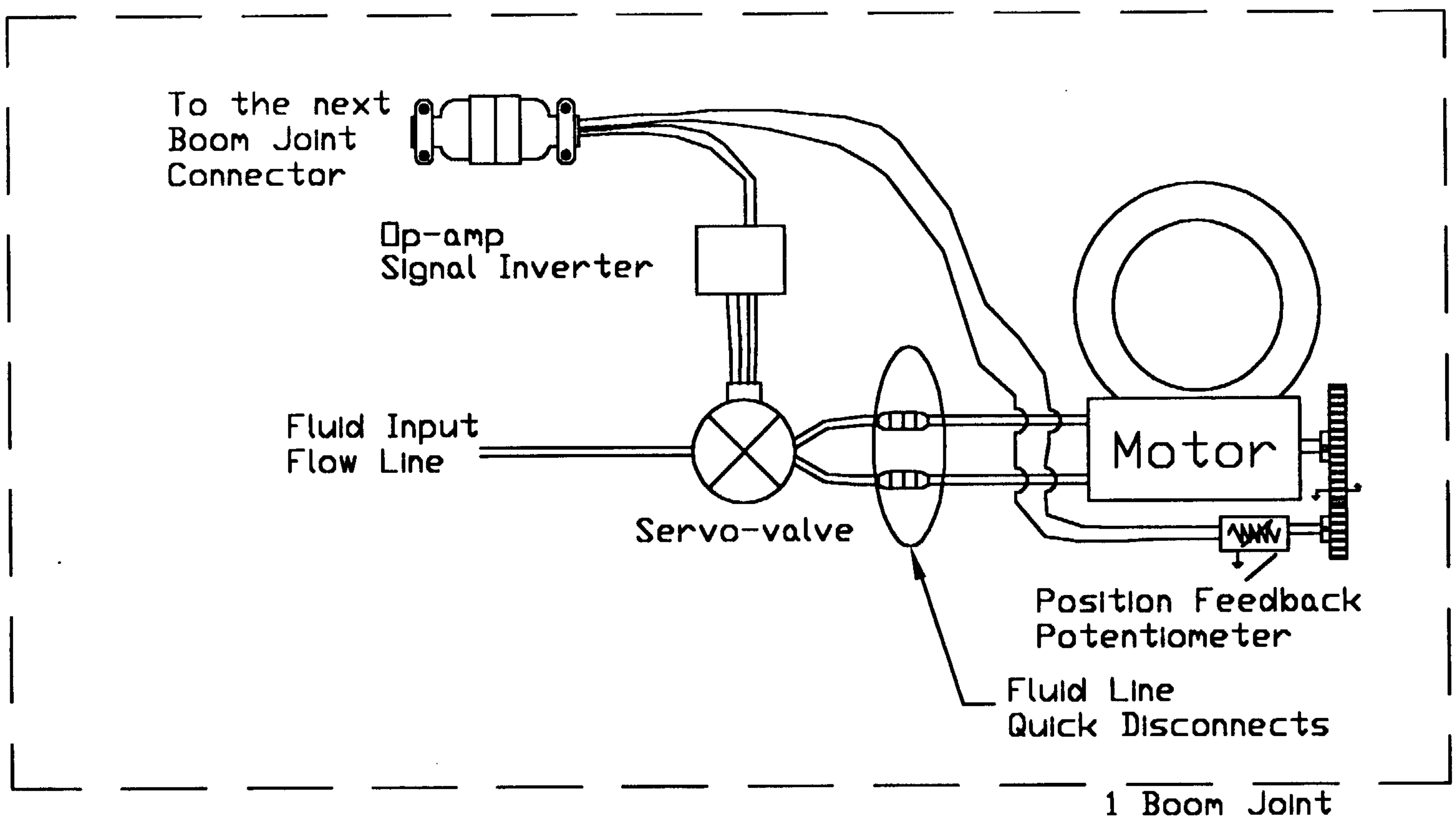


Articulate Joint 2 & 3
Rotate 180 degrees

Articulation Joints 1 & 2
Rotate 180 degrees

Toggle Switch F
Toggle Switch B

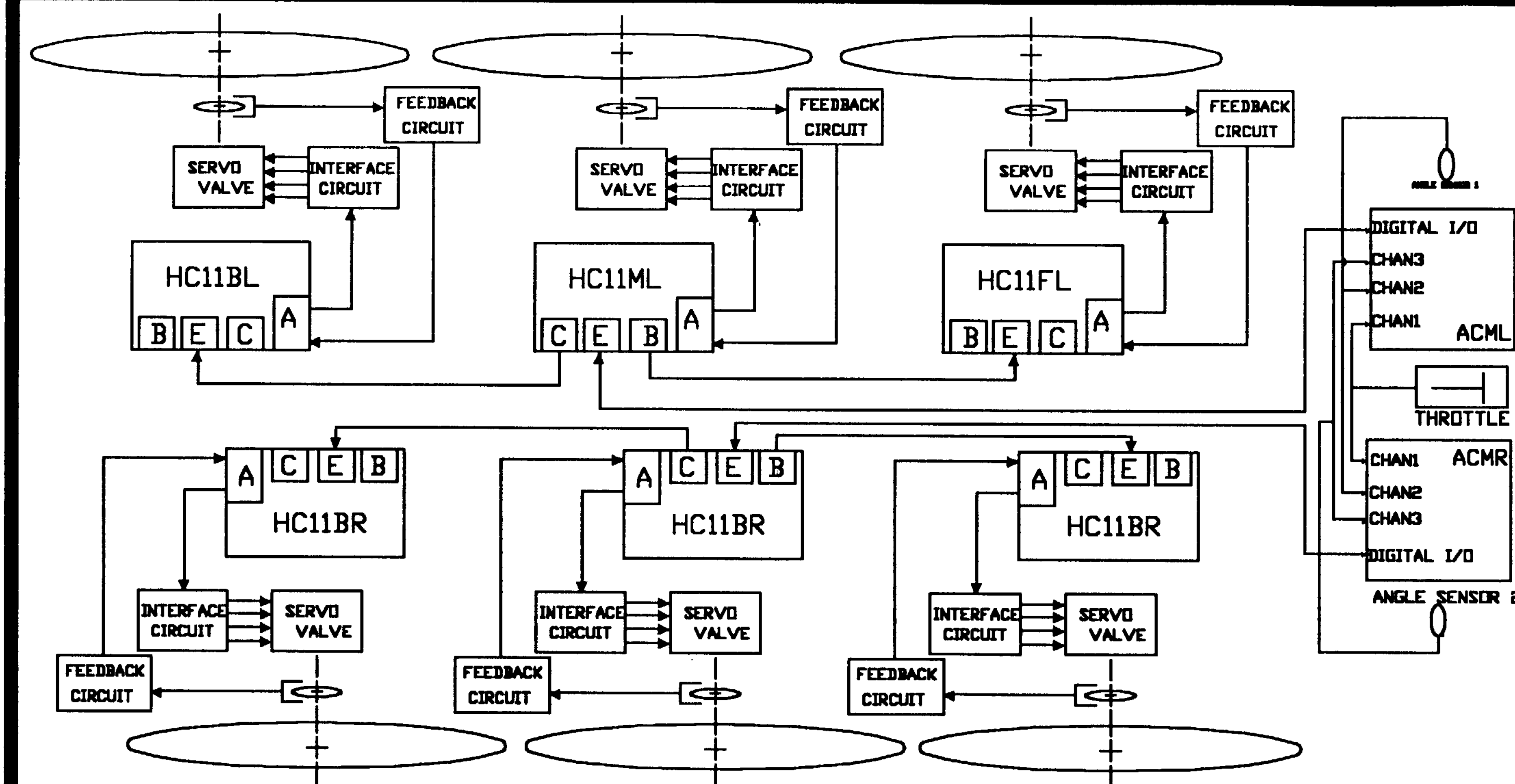
Chassis Articulation Joint Control Diagram		
Date: June 10,1992	Group Name & Number: Controls Group Group #4	
Class: ME 4182		
Professor: Brazell	Group leader initials	Support
Drawing number: D33-3	Support	Support



Notes: Drawing not to scale
Connectors are cascaded
from each boom joint

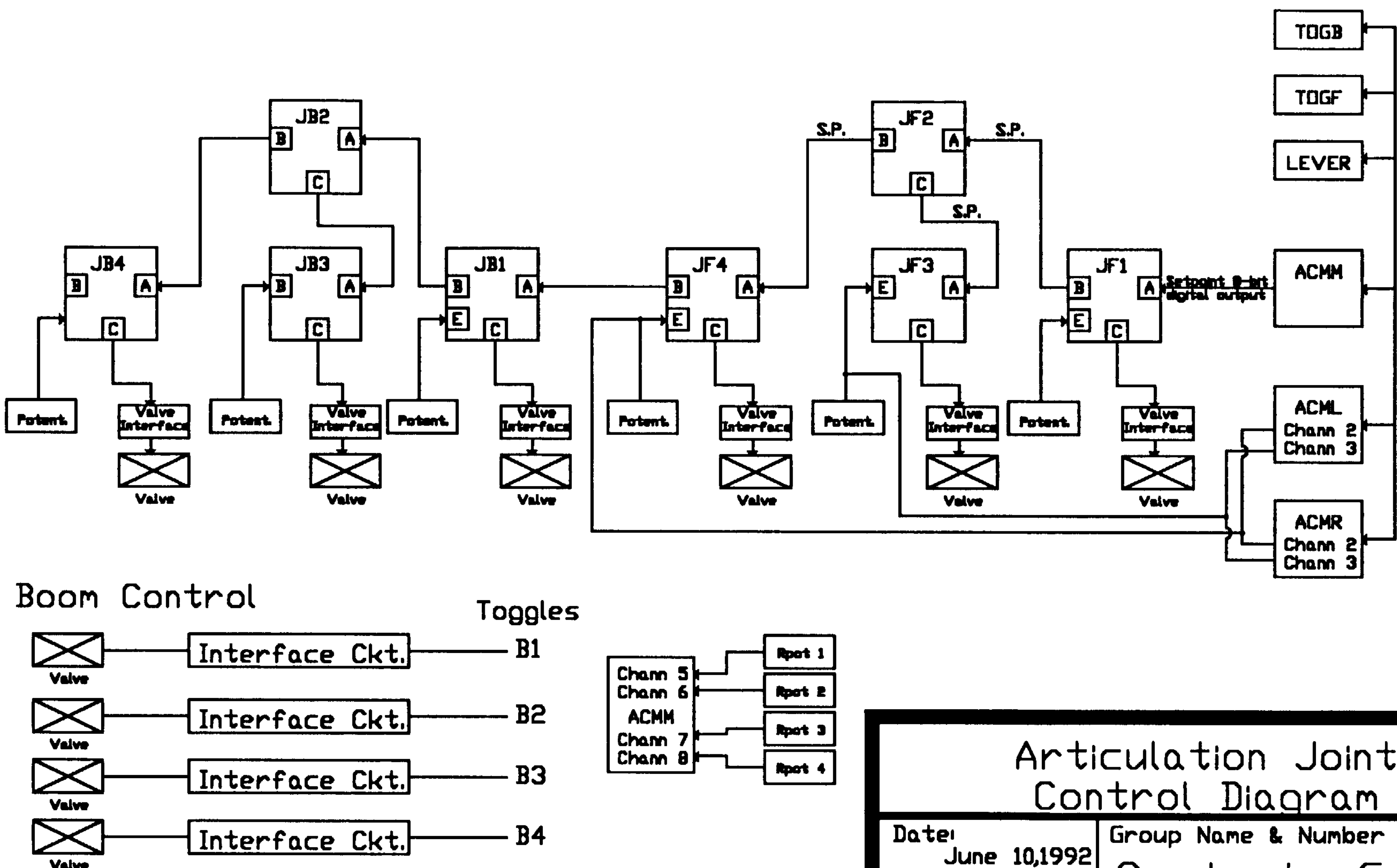
Boom Control System Layout Diagram

Date: June 10,1992	Group Name & Number: Controls Group Group #4	
Class: ME 4182		
Professor: Brazell	Group leader initials	Support
Drawing number: d34-1	Support	Support



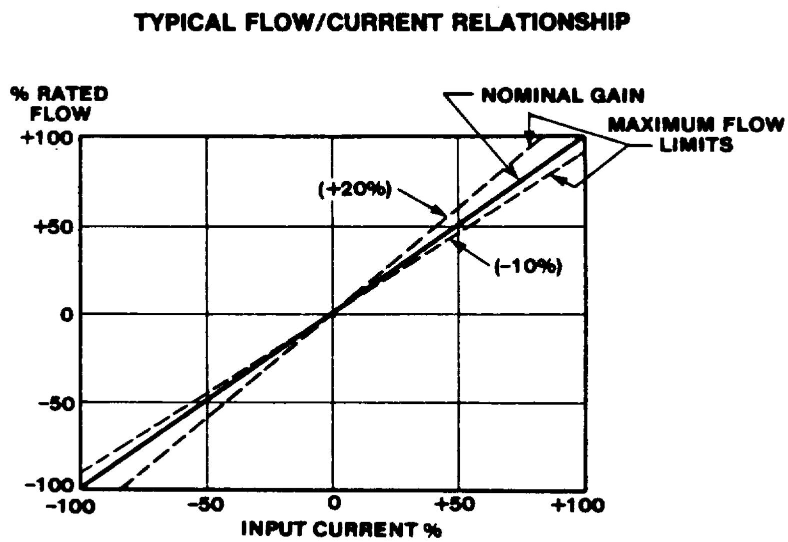
Wheel Drive Control Diagram

Date: June 10,1992	Group Name & Number: Controls Group Group #4	
Class: ME 4182		
Professor: Brazell	Group leader initials	Support
Drawing number: D35-1	Support	Support

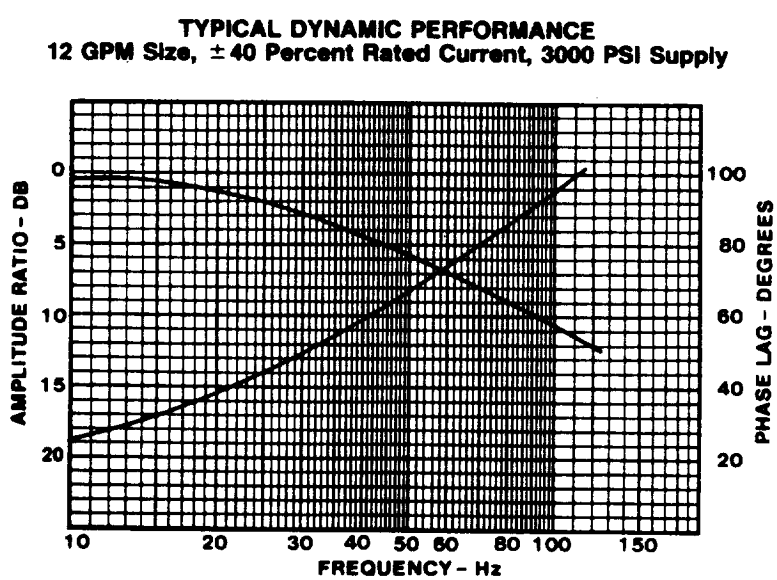


Articulation Joint Control Diagram

Date: June 10,1992	Group Name & Number Controls Group Group #4
Class: ME 4182	
Professor: Brazell	Group leader initials / Support
Drawing number: d35-2	Support / Support



Graph 1. Servo-valve Gain Performance



Graph 2. Servo-valve Time-Varying Response

Appendix B
Calculations

Gear Ratio for Potentiometers

Boom:

The Gear ratio from the worm gear to the boom joint was 63:1, thus for every 63 revolutions of the worm gear, the boom rotates one revolution. For the potentiometer to remain within the 9 turn range, then 360 degrees/9 turns = 40 degrees per one rotation of the potentiometer. Thus 63 rotations of worm gear equals 360 degrees of the boom. So, 63 rotations/9 turns = 7. So the gear ratio from the worm gear to the potentiometer needs to be 7:1.

Chassis Articulation:

The Gear ratio from the worm gear to the chassis joint was 83:1, thus for every 83 revolutions of the worm gear, the chassis rotates one revolution. For the potentiometer to remain within the 9 turn range, then 360 degrees/9 turns = 40 degrees per one rotation of the potentiometer. Thus 83 rotations of worm gear equals 360 degrees of the boom. So, 83 rotations/9 turns = approximately 9. So the gear ratio from the worm gear to the potentiometer needs to be 9:1.

Caculations for Turn Radius

per Drawing D32-4.

$\text{Cos}\ \alpha = .5*b/.9$

$r_1 = .5*b/\text{Sin}(.5\alpha)$

$r_1 = (2*0.9*0.5*\text{Cos}\alpha)/\text{Sin}\alpha$

$r1 = (2*0.9*0.5)/\text{Tan}\alpha$

$r_2 = r_1 + 1$

$r_3 + 1 = r_1$

$r_3 - r_2 = -2$

$r_3/r_2 = -(2/r_2)$

$r_3/r_2 = 1 - [(2*\text{Tan}(\Theta/2))/(1.9 + \text{Tan}(\Theta/2))]$

$k_2 = r_2/r_3$

$$k_2 = \frac{1.9*\text{Tan}(\Theta/2)}{1.9 + \text{Tan}(\Theta/2) - (2*\text{Tan}(\Theta/2))}$$

for α from 0 to 30 degrees, results presented in Table 2. Turn Radius Ratio

Appendix C
Sources

Documents

1. Newark Electronics Catalog #112, 1992.

2. Allied Electronics Catalog, 910 Engineering Manual and Purchasing Guide, 1992.

3. Hydraulics plus Electronics, Systems and Components, Catalog 400, Vickers, 1987.

4. Shigley, J.E, and C.R. Mischke, Mechanical Engineering Design, 5th Edition, McGraw-Hill, 1989.

5. Machine Design, 1990 Systems Design Reference Volume, Power and Motion Control, Penton, 1990.

6. Beckwith, T.G., and R.D. Marangoni, Mechanical Measurements, 4th Edition, Addison-Wesley Publishing Co., 1990.

7. Vito, R.P., ME3056: Experimental Methodology, Lab Manual, March, 1991.

8. M68HC11 Reference Manual, Motorola.

9. M68HC11EVB Evaluation Board, User's Manual, Motorola.

10. Del Toro, Vincent, Electrical Engineering Fundamentals, 2nd Ed., Prentice-Hall, 1986.

11. Dieter, George E., Engineering Design, A Materials and Processing Approach, 2nd Ed., McGraw-Hill, Inc., 1991.

Personnel and Companies Consulted

1. Snap-tite, Valve Division, 6424 West Ridge Road, Erie, PA, 16506-1023.

2. Vickers, A Trinova Co., 1401 Crooks Road, Troy, MI, 48084.

3. Motion Industries, Inc., 4290 Wendell Drive, P.O. Box 43965, Atlanta, GA, 30336-0965.

4. Hagglunds Denison Corporation, 425 S. Sandusky St., Delaware, OH, 43015.

5. Honeywell, Skinner Valve Division, 95 Edgewood Avenue, New Britain, CT, 06051.

6. Eaton, 26101 Northwestern Highway, Southfield, MI, 48026.

7. Ultra Fluid Technologies, Inc., P.O. Box, 30809, Columbus, OH, 43230-0809.

8. Rob Michelson, Principal Research Engineer, Aerospace Lab, GTRI.

Computer Sources

1. VSMF