Abstract

In the modern world, fossil fuels have ignited an overwhelming concern for pollutants emitted through the burning of gasoline and other non-renewable resources in vehicles, industry, and other environments. As a result of these pressing concerns, more fuel efficient hybrid electric vehicles were created, which ultimately lead to the modern day fully electric vehicles. While existing hybrids remain accessible, their complex mechanisms require the acquisition of an entirely new vehicle should an individual want a cleaner automobile. Additionally, these mechanisms coupled with the energy used, results in a fairly inefficient system. Thus, this engineering project intended on creating a true hybrid electric vehicle, in which both electrical and gasoline components were synthesized together.

Four linear actuators were used to create the electric component of a scaled version of the true hybrid engine. V4 and boxer engine configurations with different strokes were designed, implemented, and tested. These actuators were energized using switching circuit controlled via a microcontroller. Actuators were energized by varying their on-times as well as supply voltage. Test results indicated that all engine configurations are feasible for implementation within comparable voltage and on-time ranges. For the two-stroke scaled version, it was possible to achieve a maximum speed of 579 RPM. These results indicated that the creation of a true hybrid engine is feasible and will enable many to pursue cleaner alternatives to existing internal combustion engines without the costs associated to entirely new vehicles; this is because retrofitting an existing internal combustion engine would be a fairly simple process.

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1. Introduction

Early automobiles in late 1800s to early 1900s were electrically propelled. However, rapid advances in gasoline powered internal combustion engines (ICE), power density, distance travelled, and cheap mass production, resulted in a declining market for electric vehicles. For several decades economic and social growth of our society has relied on fossil fuel based transportation to move people and products. As society flourishes economically, more individuals buy cars because personal transportation offers freedom to go anywhere at any time. However, this tremendous growth in the number of fossil fuel powered cars, over the last few decades, has resulted in several key concerns related to environment and sustainability of natural resources.

It is a well-known fact that fossil fuel is a limited natural resource. According to Chris Mi et al. (Mi et al., 2011) there are approximately 1300 billion barrels of proven reserves of oil whereas the world consumes about 85 million barrels every day! Furthermore, new discoveries of oil reserves are outpaced by the rapid increase in demand. Considering the fact that transportation consumes about 60% of oil (Mi et al., 2011), reducing consumption using alternative sources of energy would improve sustainability of resources. Fossil fuels also contribute significantly to global greenhouse gas emissions and air pollution. These gases are produced from burning gasoline along with unburned fuel, and other volatile emissions ultimately affect human and animal health.

Electrically driven vehicles offer cleaner, more sustainable, and less noisy alternatives to gasoline-powered cars. However, this technology is still in its infant stage and several challenges like high cost, limited driving range, long charging times, etc. are yet to be overcome (Mi et al., 2011). In the interim period, hybrid electric vehicles (HEV) utilizing both, an ICE and electric motor, offer a viable solution resulting in significantly reduced fuel consumption compared to conventional gasoline powered vehicles (see section 2.2 for details).

This project is about creating an innovative “true” hybrid electric vehicle wherein both, electrical and gasoline powered components, are integrated into a single structure. It eliminates the need for any separate mechanical or electrical coupling mechanism. The firing of ICE cylinders and the corresponding energizing of electric linear actuators can be done using appropriately timed electrical signals generated by a microcontroller.

2. Research

2.1 Conventional Internal Combustion Engine

A reciprocating internal combustion engine (ICE) converts chemical energy produced by combustion of an air-fuel mixture in engine cylinders to mechanical energy which produces motion. The combustion causes a controlled internal explosion in a cylinder which then pushes a piston. This linear motion of the piston is translated to rotary motion to turn wheels using a crankshaft (Salazar, 1998). Depending upon the frequency of power strokes (explosions) there are two principle types of ICEs:

Four-Stroke Engine: A four-stroke ICE produces one power stroke for every four strokes during which combustion takes place. A stroke is one full travel of the piston in either direction inside the combustion chamber (i.e., the cylinder). The four strokes of a four-stroke engine are depicted in Figure 1.

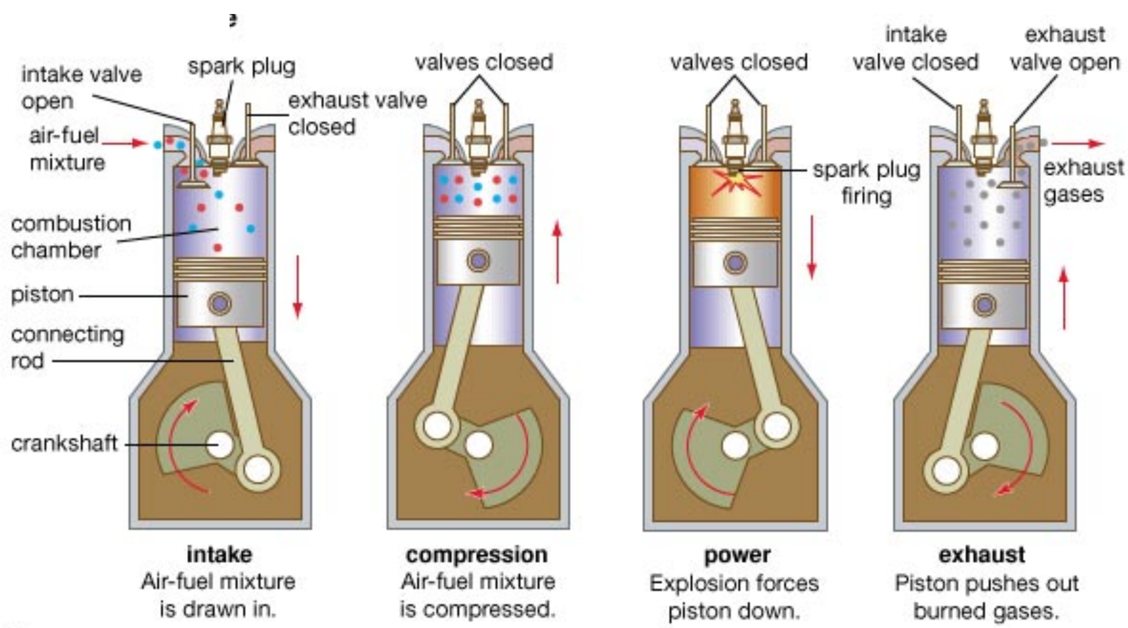


Figure 1: Four-Stroke Internal Combustion Engine (Britannica-4, 2015)

1. *Intake*: Piston stroke begins at the top and moves down sucking in an air-fuel mixture
2. *Compression*: Stroke begins at the bottom and moves up compressing the mixture
3. *Power*: Mixture is ignited (e.g., by a spark plug in gasoline engine) and the piston is forced down producing mechanical work to turn the crankshaft.
4. *Exhaust*: Piston moves from bottom to top expelling the spent mixture through an exhaust valve

Two-Stroke Engine: A two-stroke ICE produces one power stroke for every two strokes during which explosion takes place. Two strokes of a two-stroke engine are depicted in Figure 2. One revolution per cycle, where the intake and exhaust are connected to the combustion chamber.

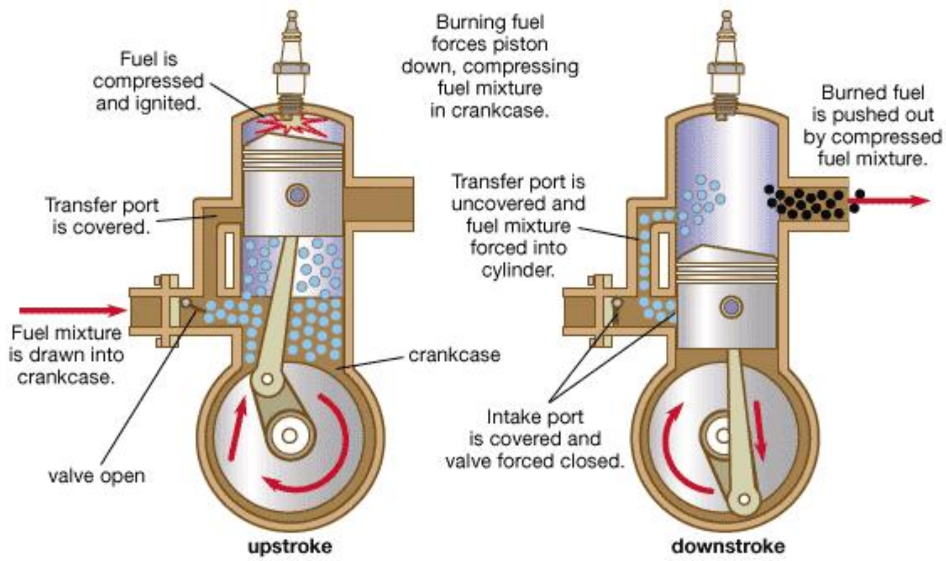


Figure 2: Two-Stroke Internal Combustion Engine (Britannica-2, 2015)

1. *Upstroke*: Fuel mixture is taken in and compressed.
2. *Downstroke*: After compression, fuel mixture is ignited and the piston pushed downwards, opening the valve to allow expulsion of exhaust.

For the same engine weight, a two-stroke engine produces more power than a four-stroke engine. However, it also emits more exhaust as the fuel burned contains oil and lubrication that are not externally present in a four-stroke engine. Usually, cars do not implement a 2 stroke engine, however they are common in applications such as motorcycles and large scale rotary movement machines.

Typically, IC engines are specified by number of cylinders, cylinder *bore* (diameter), and stroke length. These specifications determine the power output of a reciprocating IC engine. Besides individual cylinder specifications, power output, engine rpm, and torque, engine chassis vibrations are determined by the configuration of the cylinders. For example, inline engines where all cylinders are lined up in a straight line, V engines in which cylinders are arranged in a V configuration with varying V angles, boxer engines where V is flattened (i.e., V angle of 180°), radial, etc. (Car and Driver, 2011). Typical automotive engine configurations employing IC engines are depicted in Figure 3.

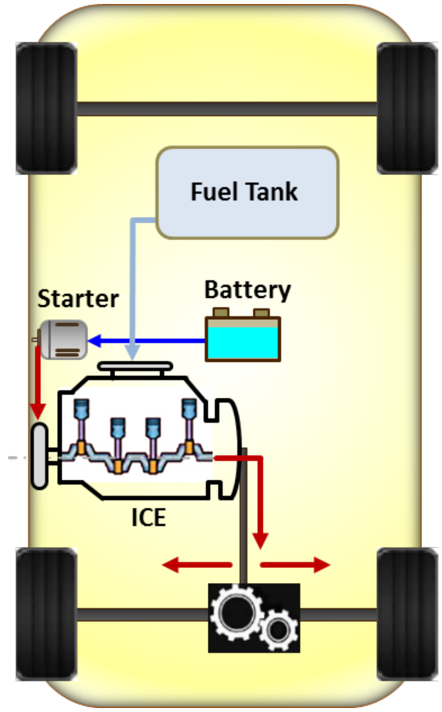


Figure 3: Conventional Automotive Internal Combustion Engine

2.2 Conventional Hybrid Engine

The hybrid engine, or HEV, combines the ICE and an Electric Motor Drive (Figure 4). The ICE powers the engine while the car is cruising, when the efficiency of the ICE is higher. When acceleration is required, the Electric Motor Drive is used because it is cleaner and more effective (Nice and Layton, 2015). However, the two engine parts do not drive the same crankshaft, nor necessarily work together at the same time.

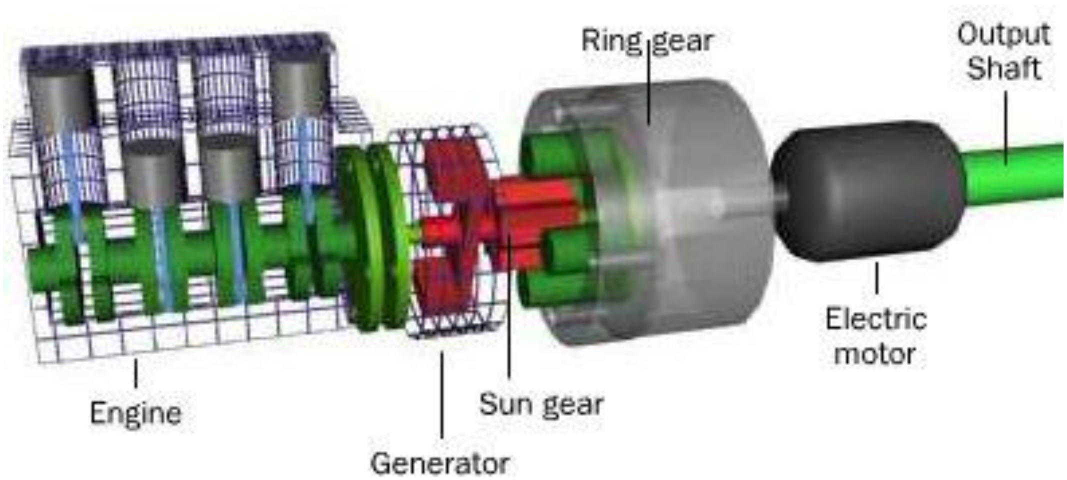


Figure 4: Conventional Hybrid Engine (Nice and Layton, 2015)

This assembly is inefficient because of the fuel and power consumption it uses. The electric motor drive engages solely in the times when fuel consumption in the ICE is very high. More so, the mechanism for this assembly is highly spacious as two engine blocks are required. Conventional HEVs can be built in two main configurations (Mi *et* al., 2011):

Series Hybrid (Extended range hybrid): The ICE turns a rotary electric generator, which then powers an electric motor that propels the wheels through a transmission system (Figure 5). That is, the ICE is not mechanically connected to the transmission directly. Alternatively, the generator charges a battery which then drives the wheels through a power control circuit. It is also called extended range hybrid because the ICE never truly drives the vehicle.

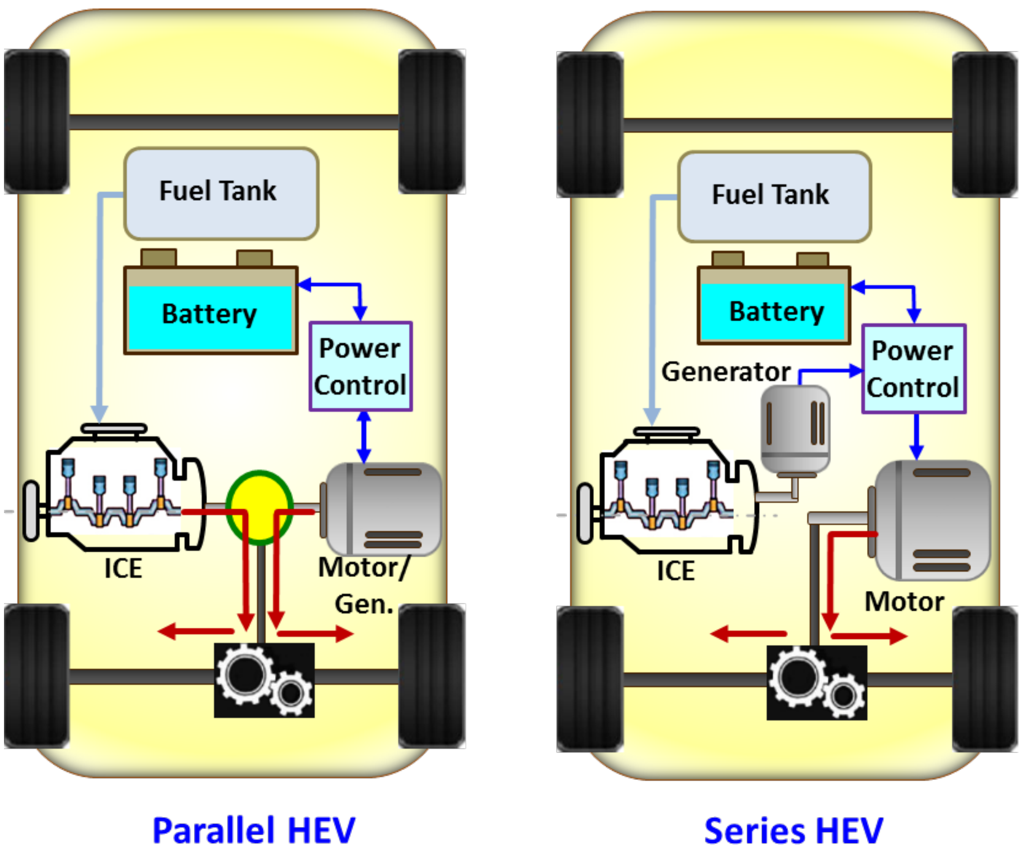


Figure 5: Series and Parallel Hybrid Engines

Parallel Hybrid: In this configuration the ICE or the electric motor drive can propel vehicle on its own separately at different times or together concurrently (Figure 5). The engine works in its optimum range for most efficiency.

2.3 Electric Linear Actuators

Reciprocating motion produced by ICE pistons can also be done using electrically energized linear actuators. In such actuators a *stator,* with conducting winding, is excited by passing current. This stator excitation creates magnetic field which results in pulling in or pushing out, a linearly moving *armature*. There are several types of electrical linear actuators: solenoids, linear dc motors, linear switched reluctance motors, etc. Actuators can be chosen based on applications, need for speed control, direction of motion, force requirements, etc. In the scaled prototype designed and implemented in this project, solenoids are used as a form of a linear actuator to create reciprocating motion.

Solenoid:

A solenoid consists of a conducting winding mounted on a stator (mounted inside a casing) and linearly moving plunger called armature (Figure 6). When current does not flow through the coil the armature does not move (Figure 6a). When current is supplied to the coil, magnetic field is created through the coil as per Ampere's Law. This magnetic field results in pushing out (or pulling in) the armature with force *F* (Figure 6b) creating linear motion (Bicron, 2015).

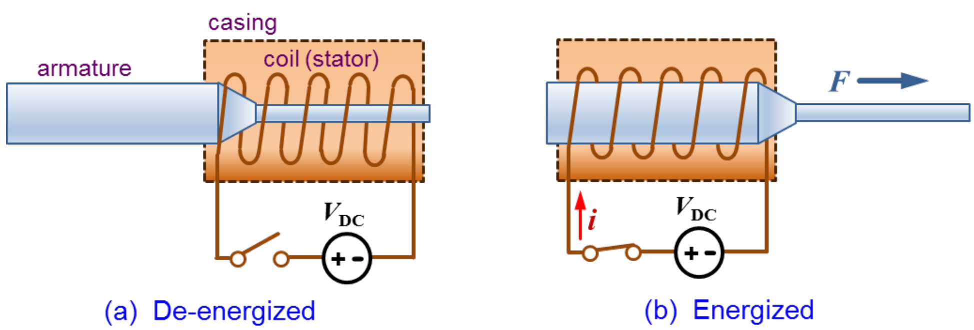


Figure 6: Unidirectional Solenoid Linear Actuator

There are two types solenoids based on linear motion produced: (i) *Unidirectional* solenoid in which the armature moves in one direction when energized as shown in Figure 6; (ii) *Bidirectional* solenoid in which armature can be moved actively in both directions. A unidirectional solenoid needs a separate mechanical mechanism (a spring or some externally applied force) to move the armature back to its original de-energized position. A bidirectional solenoid uses two coils, which are energized alternately to move the armature back and forth. The solenoids used in this project are unidirectional solenoids. For current, i, flowing through the coil, distance, X_S, traveled by the armature, change in inductance (ΔL) of the coil, force produced is:

$$Force = \frac{1}{2} \cdot I^2 \cdot \frac{\Delta L}{X_S}$$

2.4 Control of Actuators

Linear actuator shown in Figure 6 is energized by turning on a switch. When this switch is turned off the actuator is de-energized. In order to do this quickly, this switch can be implemented using an electronic switch like a MOSFET that is controlled using digital signals produced by a microcontroller. Several different microcontrollers can be used. Currently, one of the most popular and easily available microcontrollers for these kinds of applications is the Arduino UNO. It is relatively easy to learn how to program and can be used for different applications (Timmis, 2011, Durfee, 2011). In this project, the Arduino UNO was used to generate control signals for the electronic switches.

Due to the inductance of the coil, one has to be careful when an actuator is de-energized. It is a property of an inductor to oppose any change is current by inducing voltage to oppose this change. The magnitude of this induced voltage is proportional to the value of inductance and the rate of change of current. When the switch is turned-off to de-energize an actuator, current flow is suddenly turned-off, i.e. rate of change of current is large due to which large voltage is induced which is hazardous. Energy stored in the inductance of the actuator coil hence has to be expended. A simplest way to achieve this is by using a single electronic switch (MOSFET) as shown in Figure 7.

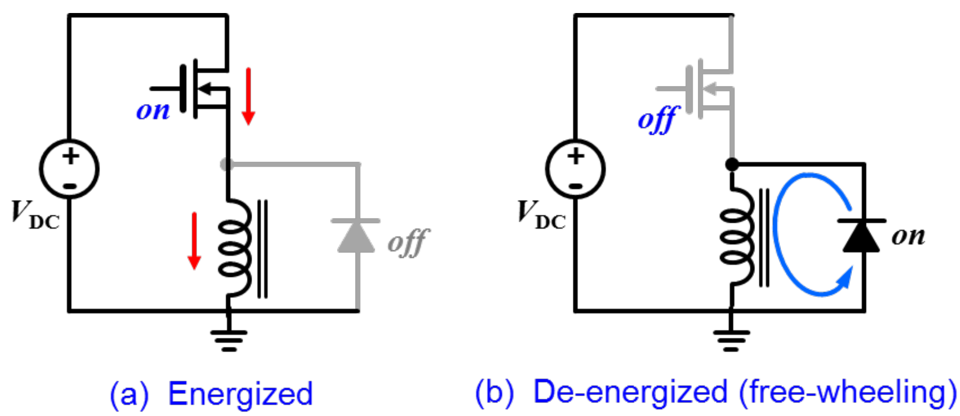


Figure 7: Linear Actuator using a Single Switch and Diode

In Figure 7(a) when the MOSFET switch (Nmosfet, 2013) is turned-on current flows through the actuator coil, energizing it. The diode across the coil is off since its cathode terminal is positive with respect to its negative terminal. When the switch is turned-off to de-energize the actuator, since current through the inductance of the coil cannot change suddenly, it continues to flow in the same direction because now the diode is turned-on. This enables the energy stored in the coil to be expended until the actuator is fully discharged through the diode. Diode used in this fashion is referred to as, *free-wheeling diode* (Rahimo and Shammas, 2001). Discharging inductance of the coil in this fashion is similar to driving a wheel using a motor then disconnecting the motor and allowing the wheel to come to rest on its own when it runs out of stored energy. Alternatively, if this wheel's energy is transferred to some other mechanism, it will come to rest faster. This can be done using more than one electronic switches and diodes enabling actuator coil to de-energize faster as shown in Figure 8.

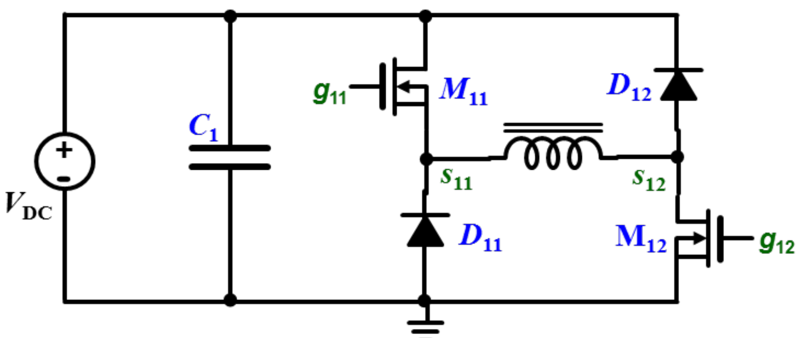


Figure 8: Actuator Control using Asymmetric Full-Bridge

Asymmetric full-bridge shown in Figure 8 energizes the actuator by turning-on MOSFET switches M_{11} and M_{12} by driving the gate signals, g_{11} and g_{12} as depicted in Figure 9(a). Current flows (shown by red arrows) from terminal s_{11} to s_{12} of the actuator coil, energizing it. Actuator is de-energized by turning-off M_{11} and M_{12} as shown Figure 9(b). Current direction through the coil is kept unchanged using the diodes D_{11} and D_{12} as shown by red arrows in Figure 9(b). Energy stored in the coil is expended rapidly by discharging it into the power supply V_{DC} capacitor C_1 charging it to help provide energy for the next energizing cycle. Alternatively, energy can be partially sent back to the source to be stored in a battery. This technique enables relatively rapid de-energizing of the actuator coil compared to the single switch and free-wheeling diode circuit shown Figure 7.

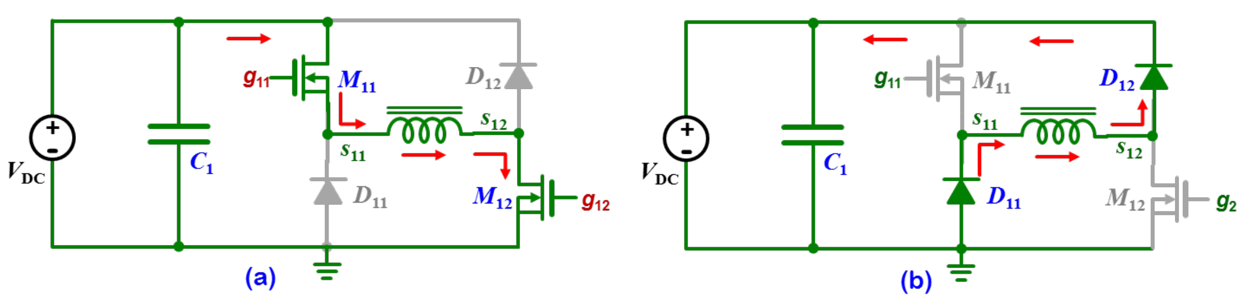


Figure 9: Energizing and De-energizing Actuator using Asymmetric Full-Bridge

3. Engineering Goals

The main goal of this engineering project was to propose an innovative true hybrid engine, in which the electric and internal combustion engine is synthesized on one crankshaft. Electric component for a "true" hybrid engine (True-HEV) was designed and implemented. This electric component of the proposed True-HEV is compatible with pistons (cylinders) in an ICE such that some of the cylinders of an ICE can be replaced by this electrical system developed here and the rest of the ICE system remains unchanged. This scaled electric component of the True-HEV was implemented by electric linear actuators so that it can be integrated on the same crankshaft as the ICE to convert reciprocating motion to rotary motion.

The project goals were achieved specifically through:

- *Engine Movement*: The function of the electric engine should be similar to the conventional IC engine, where reciprocating movement is converted to rotary movement via crankshaft.
    - Utilize four independent linear actuators to provide reciprocating (linear) motion needed for a four-cylinder engine.
    - Design and construct a crankshaft to convert linear reciprocating motion to rotary motion.
- Test and characterize the constructed, scaled prototype for metrics such as speed (revolution per minute (RPM)), voltage, current, and timing signals for actuators (solenoids) in different configurations.
- Propose a complete True-HEV system to combine the above electric engine with a conventional ICE. Basic idea of this True-HEV is depicted in Figure 10.

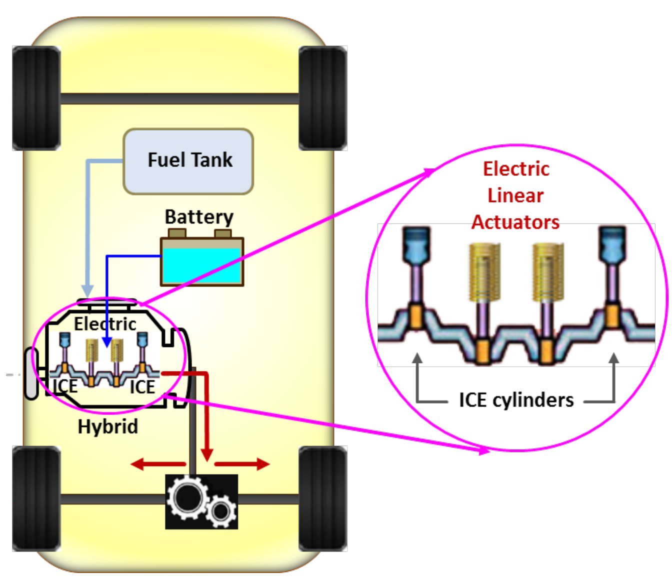


Figure 10: Conceptual Depiction of the True Hybrid Engine

4. Design Specifications

Mechanical System:

- Build a 4-cylinder scaled prototype engine in V4 (V angle of 90°) and boxer (V angle of 180°) configuration
- Construct appropriate crankshaft for this engine; use different stroke lengths. The crankshaft must be positioned accurately such that the power stroke of the solenoids are converted to a smooth rotational movement.
- Proper placement of actuators is necessary alongside with a balanced energizing order for each actuator such that the crankshaft receives a balanced force.

Electronics:

- Design appropriate drive circuits to energize and de-energize the high power actuators using low power control signals produced by a microcontroller.
- Drive circuit components should be appropriate to provide the necessary power to energize the actuators and to rapidly de-energize them.

Control System:

- Use Arduino microcontroller to generate actuator control signals in correct sequence so as to turn the crankshaft without any back and forth oscillations to minimize torsional vibrations of the crankshaft.
- Utilize pulse width modulation technique through the programmed microcontroller to change "on-time" interval of each actuator to vary speed of the overall engine

5. Materials

- Solenoids (×4): Guardian Electric TP12x19-I-24 VDC
- Arduino UNO board (microcontroller) with AA battery pack
- Electronic Components:
    - MOSFETs: TK33S10N1ZLQTR-ND (×8)
    - Diodes: VB20100S (×8)
    - Gate Drivers: TLP250 (×8)
    - Line Drivers: ACT244 (×2)
    - Capacitors: 10μF (×8), 0.1μF (×7), 560μF
    - Resistors: 1kΩ (×16), 10Ω (×8)
    - Potentiometer: 1kΩ

    - 2-pin screw terminals (×2)
    - Circuit board, soldering iron
- Power Supply (0-20V DC)
- Digital multimeter
- Crankshaft materials
    - 90° Aluminum brackets (×7)
    - 4mm and 5mm diameter All-thread (1m) with 48 fastening nuts
    - 5mm thick, 2cm wide aluminum strip for connecting rod
    - 3mm thick, 1.1cm wide aluminum strip for torque arm
    - 4mm and 5mm dia. shaft ball bearings
- Engine chassis
    - 51cm × 25cm wooden board for base
    - 38cm × 8cm × 1cm (×2) and 14cm × 7cm × 3cm (×4) wooden boards for actuator mounts
    - 5cm long wood screws (×8)
- PC to develop Arduino program and also for testing the circuit.

6. Procedure

Actuator Characterization:

Before designing the linear actuator (solenoid) based engine, characterize each solenoid to determine its inductance and the force produced when it is energized:

1. Connect the 0-20V power supply (VDC) to the two terminals of an actuator.
2. Completely pushed the actuator armature inside. This determines the starting position of the actuator. Measure its inductance at this position
3. Turn on the VDC and slowly increase the supply voltage from 0V towards 20V and stop at the point where the actuator is energized and the armature is fully pushed out. Record this minimum voltage and the corresponding current (I). Measure the inductance (L) at the final position. The difference between final and start positions is the distance travelled by the armature or its stroke length (X_S).
4. Vary the stroke length by changing the starting position of the armature by not fully pushing it in. Repeat step 3 for each stroke length.
5. Compute force produced for each stroke length using the following:

$$Force = \frac{1}{2} \cdot I^2 \cdot \frac{\Delta L}{X_S}$$

where, current is in Amperes, change in inductance is in Henrys, stroke length in Meters, and force is in Newtons.

Preliminary Engine Designs:

Before designing the four-actuator electric engine, several preliminary designs were done using two actuators. This was done to fully understand the mechanical movement, requirements for electrical actuation in presence of load provided a second actuator, and design of electronic drive circuit to provide the necessary actuator drive signals.

1. ***Reciprocating motion with two actuators and manually switching***: Two actuators were placed end-to-end as shown in Figure 11. Since the actuators used in this project are unidirectional solenoids, they need externally applied force to put the armature back to its de-energized position. However, when this is done, the solenoid should be first electrically de-energized. In Figure 11 two solenoids are used as follows: when one is energized the other is de-energized. The energized one pushes its armature out which applies force to the armature of the other de-energized solenoid pushing it back to its initial position. This repeats creating a back-and-forth reciprocating motion. The switching was done using a single pole double throw switch to connect VDC to one solenoid at any given time.

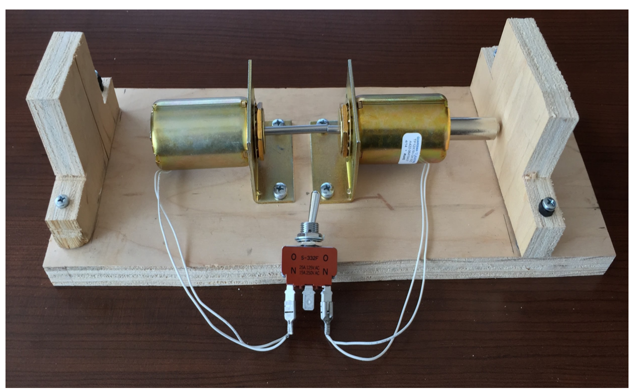


Figure 11: Manually creating reciprocating motion with two solenoids

2. ***Reciprocating motion with two actuators and electronic switching***: The two-actuator assembly shown in Figure 11 was enhanced by using electronic switching depicted in Figures 7-9. This version of design is shown in Figure 12. Time taken to energize and de-energize an actuator was observed from the charging and discharging time of the actuator coils. These results are presented in the results section of this report. These electronic switching circuit was controlled using 0-5V pulses generated by the Arduino UNO microcontroller.

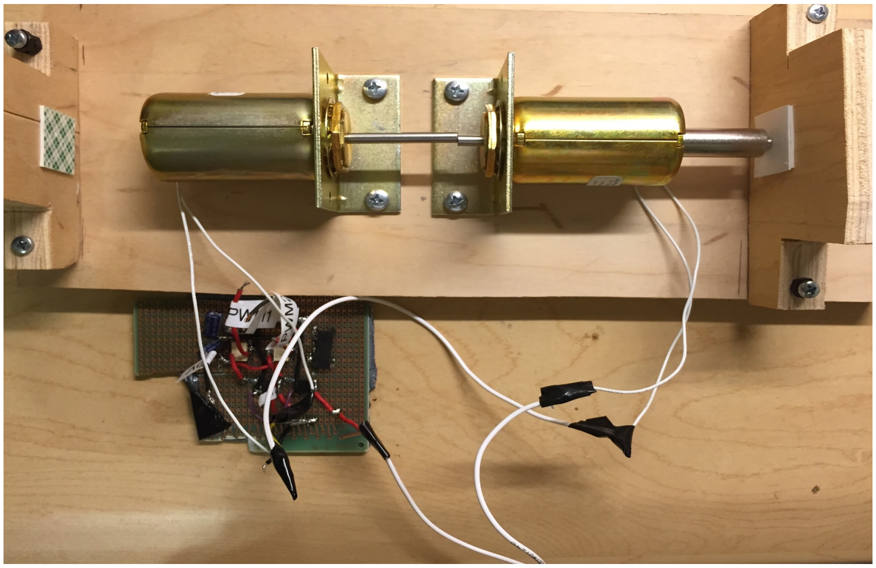


Figure 12: Two solenoids controlled using electronic switching

3. ***<u>Reciprocating motion converted to rotary motion</u>*:** Two solenoid structure shown in Figure 12 was further enhanced by introducing a preliminary crankshaft created using wheels and shafts from existing Meccano spare parts. This preliminary version is shown in Figure 13. This approach of creating crankshaft using wheels with nuts and bolts could not provide smooth rotary motion. Tightening of screws during operation created resistance to motion which sometimes resulted in rocking and even stalling of the crankshaft.

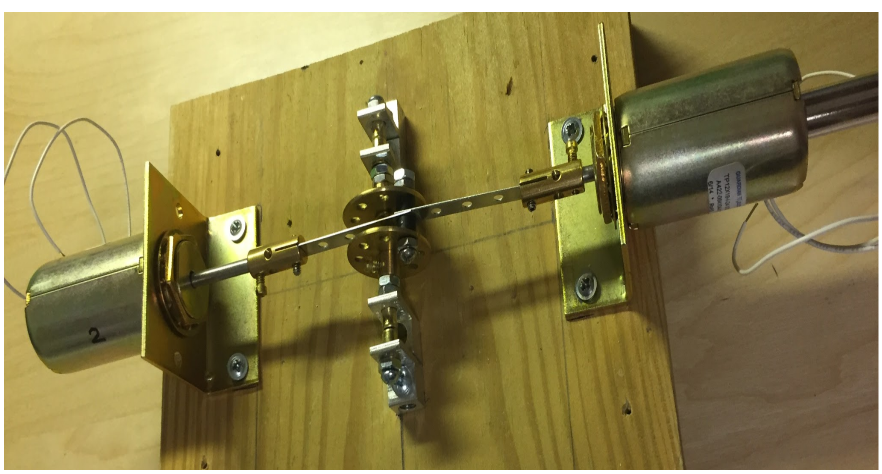


Figure 13: Two solenoids controlled using electronic switching

Four-Actuator Electric Engine:

Using the results of preliminary engine design experiments, actuator characterization data, and electronic drive circuit experiments a four-actuator electric engine which works like a four-cylinder ICE and which can be easily integrated together can be created using the following procedure.

A. Crankshaft Construction:

1. *Manually cut crankshaft pieces*: Use 3mm and 5mm thick aluminum strips to cut pieces for torque arms and connecting rods using the design drawings given in Figure 14. The actuator to connecting rod coupling was taken from existing Meccano spare parts. When these manually cut pieces were assembled together along with other engine parts the resulting assembly was not moving freely and at times getting stuck.

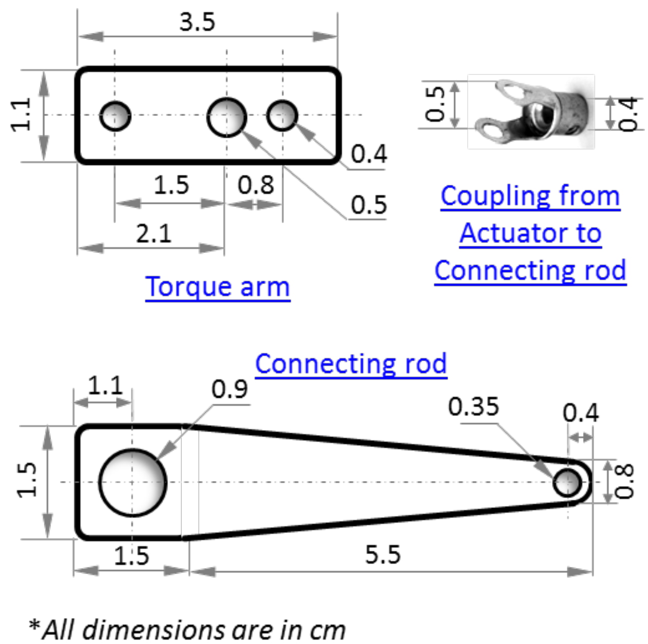


Figure 14: Crankshaft components design

2. *CNC cut crankshaft pieces*: Since a four-actuator engine operation relies on several interconnected parts for its smooth operation, precise cutting and alignment of each part with respect to others is important. A computer numerical control (CNC) machine can be employed to do precision cutting of these part. Final version of the crankshaft parts were cut by a CNC machinist at a local workshop. These parts were then manually smoothened by sanding and removing sharp and rough edges. Final assembly of one connecting segment of the crankshaft is shown in Figure 15.

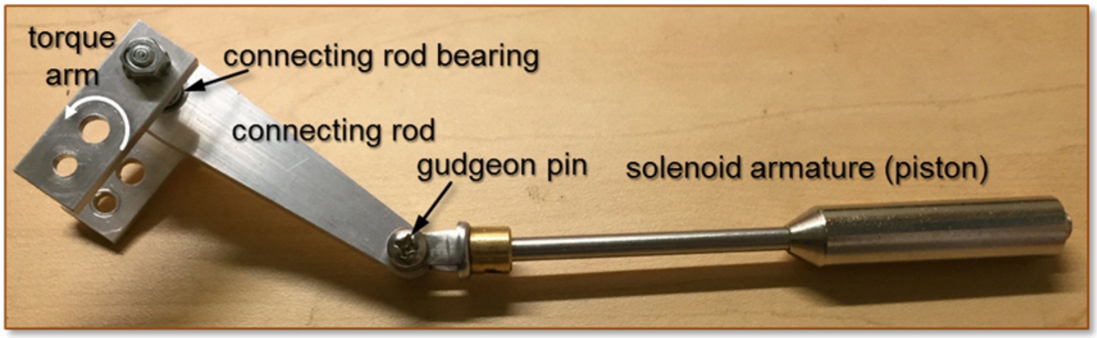


Figure 15: Crankshaft connecting assembly

3. Cut crankshaft supports from 90° aluminum brackets as shown in Figure 16.

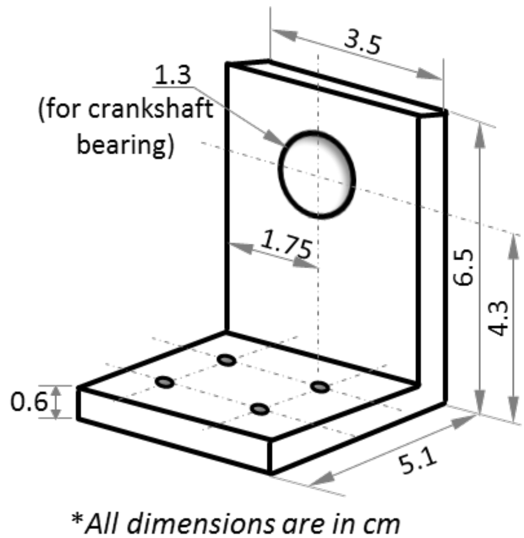


Figure 16: Crankshaft support design

4. Layout all the crankshaft segments with all-thread shafts and respective lock nuts as shown in Figure 17.

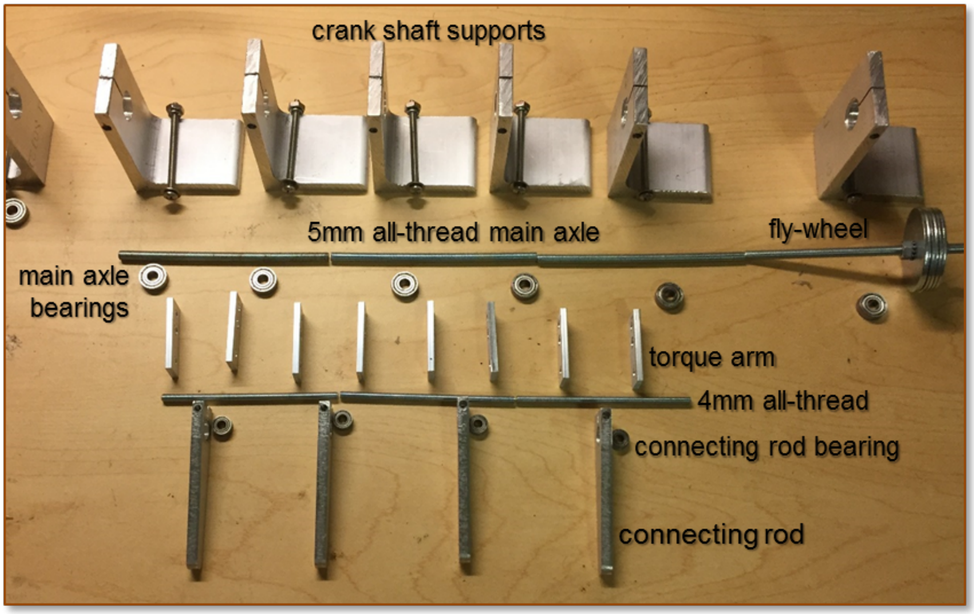


Figure 17: Components for the crankshaft assembly

5. Place shaft bearings in the crankshaft support and in the connecting rods. One assembled crankshaft segment is shown in Figure 18.

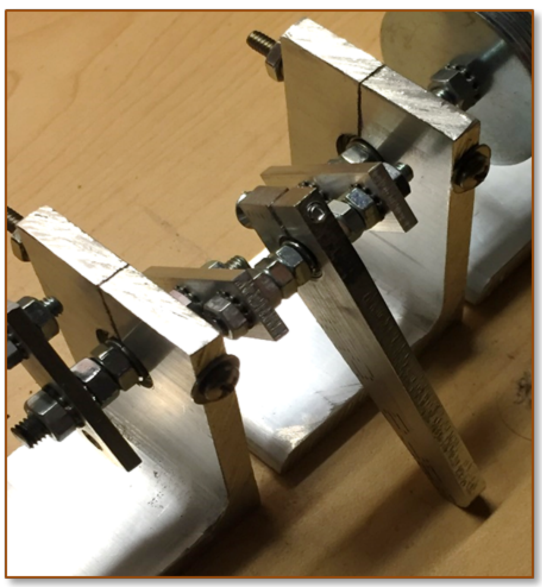


Figure 18: One crankshaft segment showing assembly details

6. Assemble the crankshaft as shown in Figure 19. Orient the cranks with a 180° offset between cranks 1 and 2, and 3 and 4 as shown as shown in the line drawing.
7. Fasten the center axle within the bearing placed in the crankshaft supports.

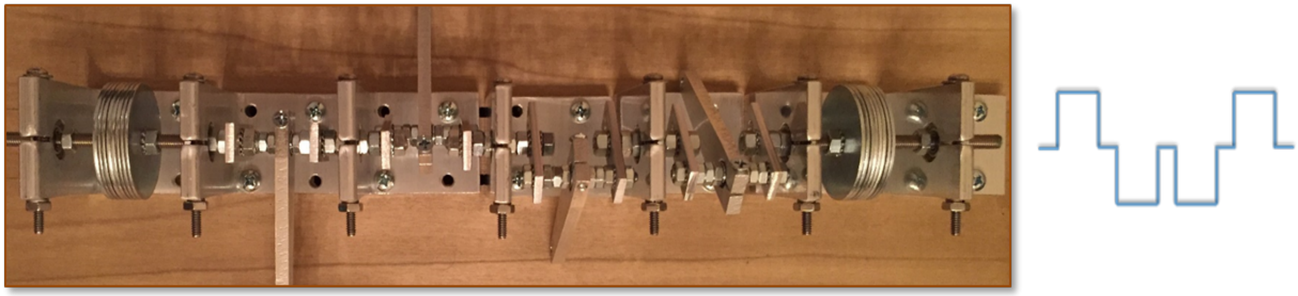


Figure 19: Assembled crankshaft for a four-actuator electric engine

B. **Engine Chassis Construction:**

1. For a V4 engine (V angle of 90°) cut out wooden engine mounts as shown in Figure 20. For a boxer engine (V angle of 180°) these mounts are not needed.

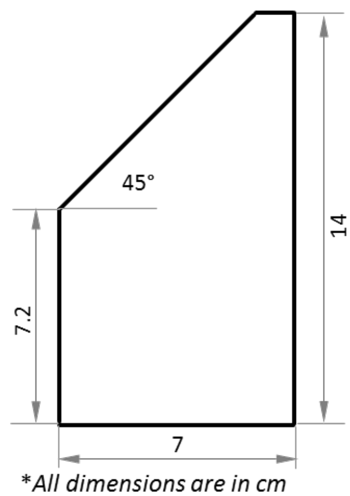
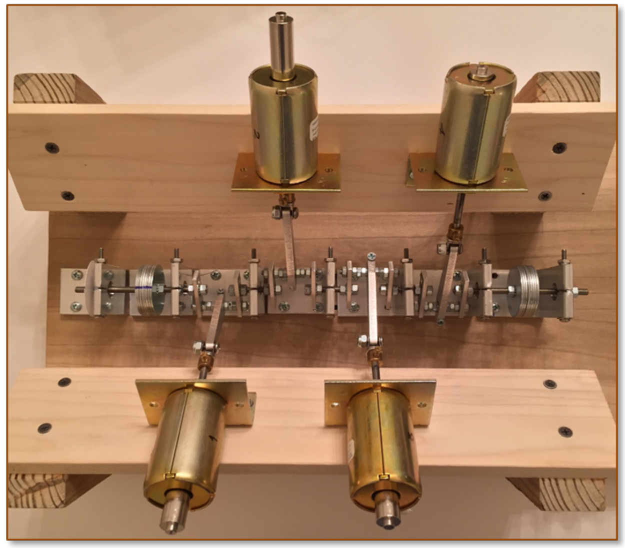


Figure 20: V4 engine mount for V angle of 90°

2. Align and drill necessary holes on each of the 38cm × 8cm boards to mount the solenoids. Stagger the position as needed to fit the solenoids (two per board).
3. Secure each solenoid to the holes via bolts and nuts.

4. Place the mounted solenoids on the two pairs of engine mounts built in step 1 above and attach them to the engine base (the 51cm × 25cm wooden base board).
5. Complete mechanical assembly of V4 electric engine is shown in Figure 21.
6. Top view of the boxer configuration for this electric engine is shown in Figure 22. In the boxer engine the actuators are placed flat on the base of chassis, i.e., the V angle is now 180°.

side view



top view

Figure 21: Complete assembly of V4 electric actuator engine

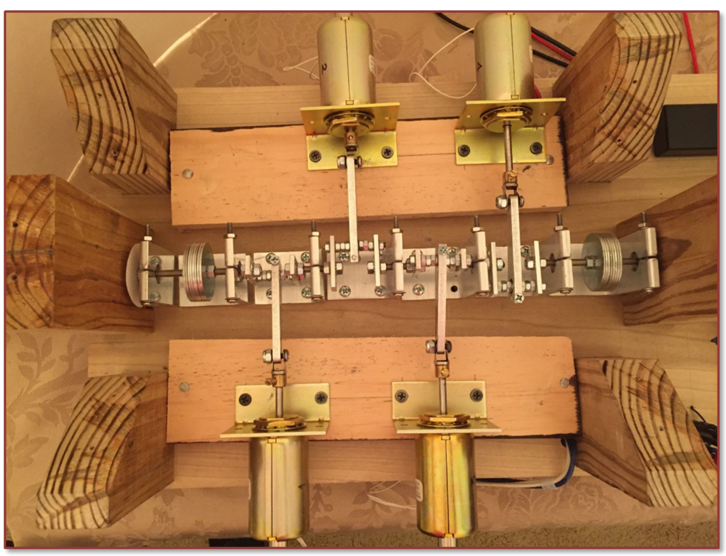


Figure 22: Top view of the boxer configuration of the electric actuator engine

C. **<u>Drive Circuits for the Actuators (Solenoids)</u>:**

1. Overall electromechanical system is as shown in Figure 23 where an energizing circuit comprising of four drive circuits energize / de-energize each of the four actuators as shown in Figure 24. Capacitance C_1 is used to smoothen out any supply voltage ripple and to store return energy from solenoids when they are discharged.

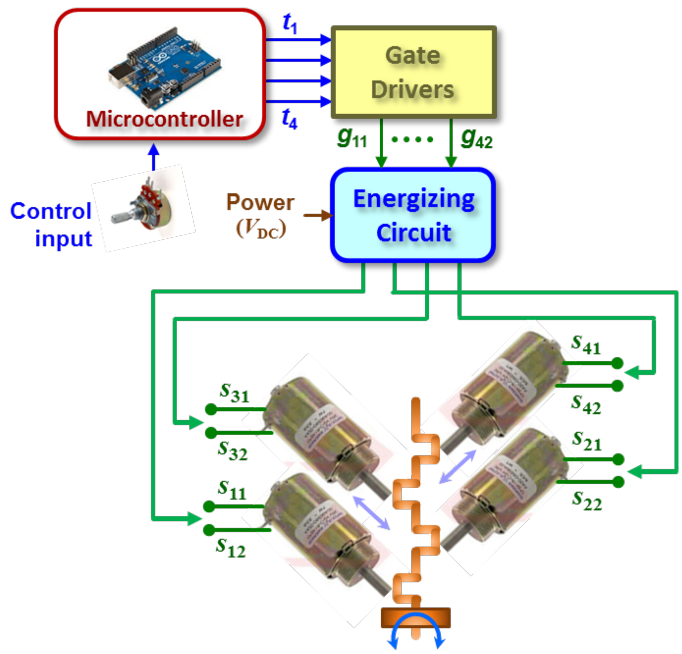


Figure 23: Overall electromechanical system

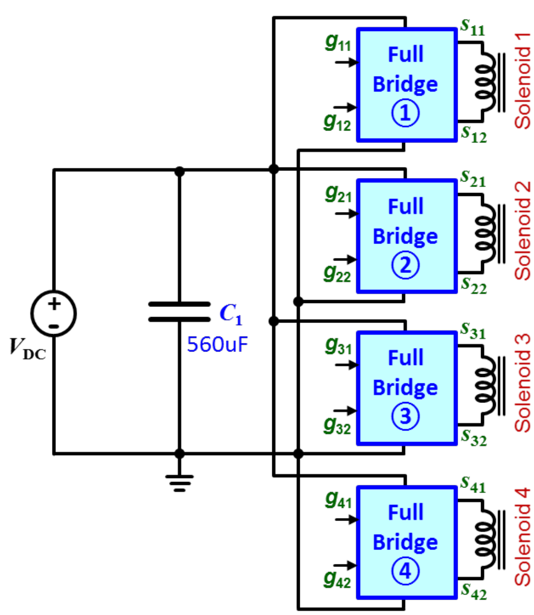


Figure 24: Energizing circuit for the actuators (solenoids)

2. Each actuator drive circuit is implemented as an asymmetric full (H) bridge as shown in Figure 25 for solenoid 1. Use two MOSFET switches (Nmosfet, 2013) and two diodes to create each drive circuit. Note, only one capacitor C_1 is used for the combined drive circuits. Operation of this circuit was discussed earlier in this report in Figure 9.

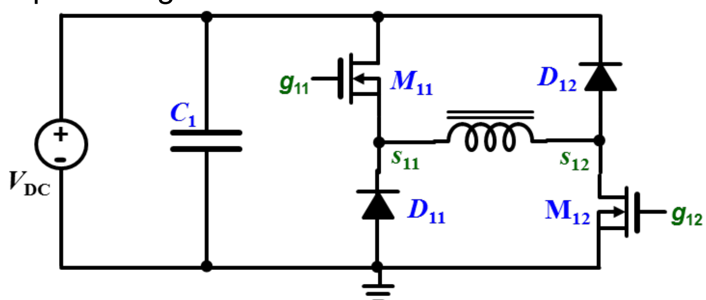


Figure 25: Asymmetric full bridge drive circuit for solenoid ①

3. Each full bridge switch is driven by gate signals (g_{11}, g_{12} for solenoid 1 shown in Figure 25) which are generated by gate driver circuit. Implement the gate driver circuit shown in Figure 26.

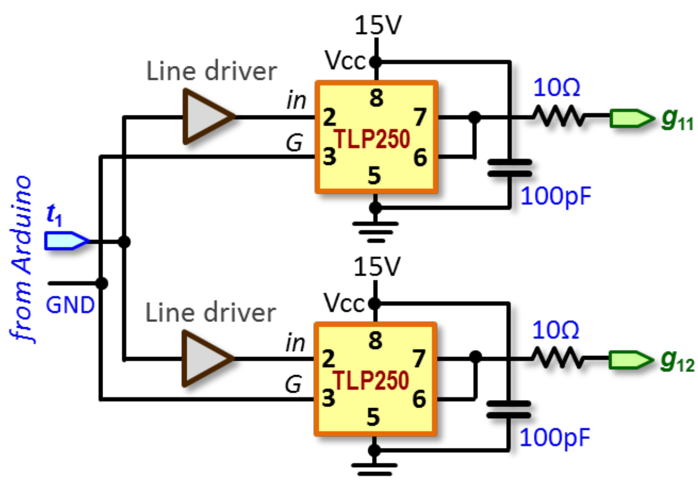


Figure 26: Gate drive circuit for full bridge①

4. Opto-coupled gate drivers (TLP250, 2004) are used in this project to provide galvanic isolation between the low voltage side (Arduino) and the high voltage (MOSFET switches) side. Line drivers are used to enhance drive capability of low voltage signals from the Arduino microcontroller.
5. Implement the full bridge and gate driver circuit combination for all the four actuators (solenoids).
6. Ensure that power supplies to energize driver circuits and actuators are separate. Provide a fixed 15V supply for the control circuit and a variable supply (VDC) to the actuators (solenoids).

7. Preliminary version of the electronic switching circuit design described earlier was implemented using a manually wired soldered prototyping board. Final design was implemented using auto placed and routed double-sided printed circuit board which can be design using any PCB design tool.
8. Each gate driver circuit is excited by the corresponding control signal (t) generated by the Arduino microcontroller as shown in Figure 26, i.e., signal t_1 for full bridge 1.
9. Connect Arduino microcontroller to all the actuators' gate drivers (t_4 t_3 t_2 t_1) as shown in Figure 27.

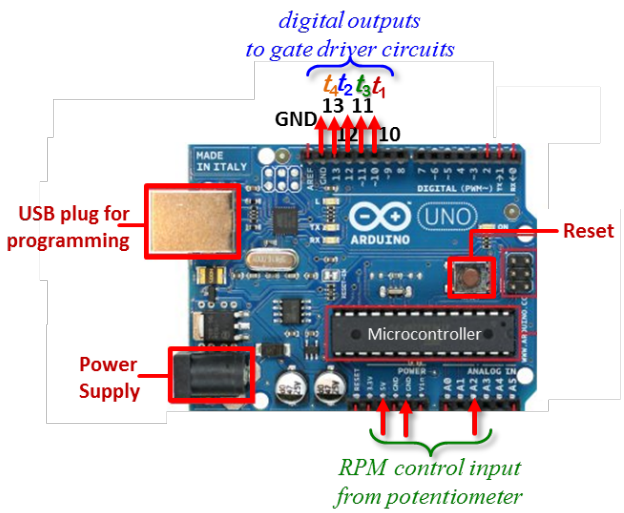


Figure 27: Microcontroller connections

10. Check connectivity of all connections using a multimeter. Figure 28 depicts the complete circuit board showing four microcontroller inputs, four output pairs for solenoid connections, VDC and 15V power supply connections.

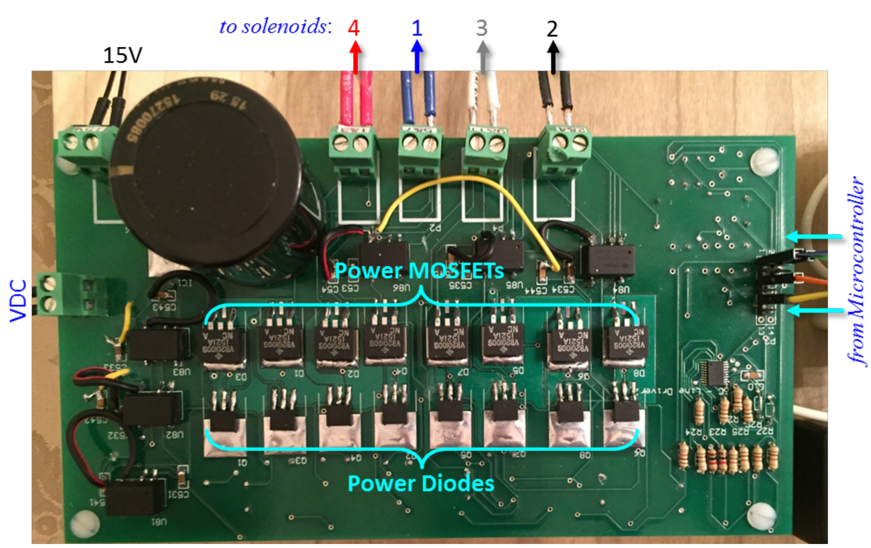


Figure 28: Circuit board for actuator driving circuits

11. Attach all the armatures securely via connecting rods to the crankshaft. Tightly secure all nuts. Connect all actuators to appropriate drive circuit connections on the board shown in Figures 27 and 28.
12. Complete V4 electric actuator (solenoid) engine (with V angle of 90°) as shown in Figure 29.
13. The boxer engine configuration shown in Figure 22 can be connected in the same way to the drive circuit board.

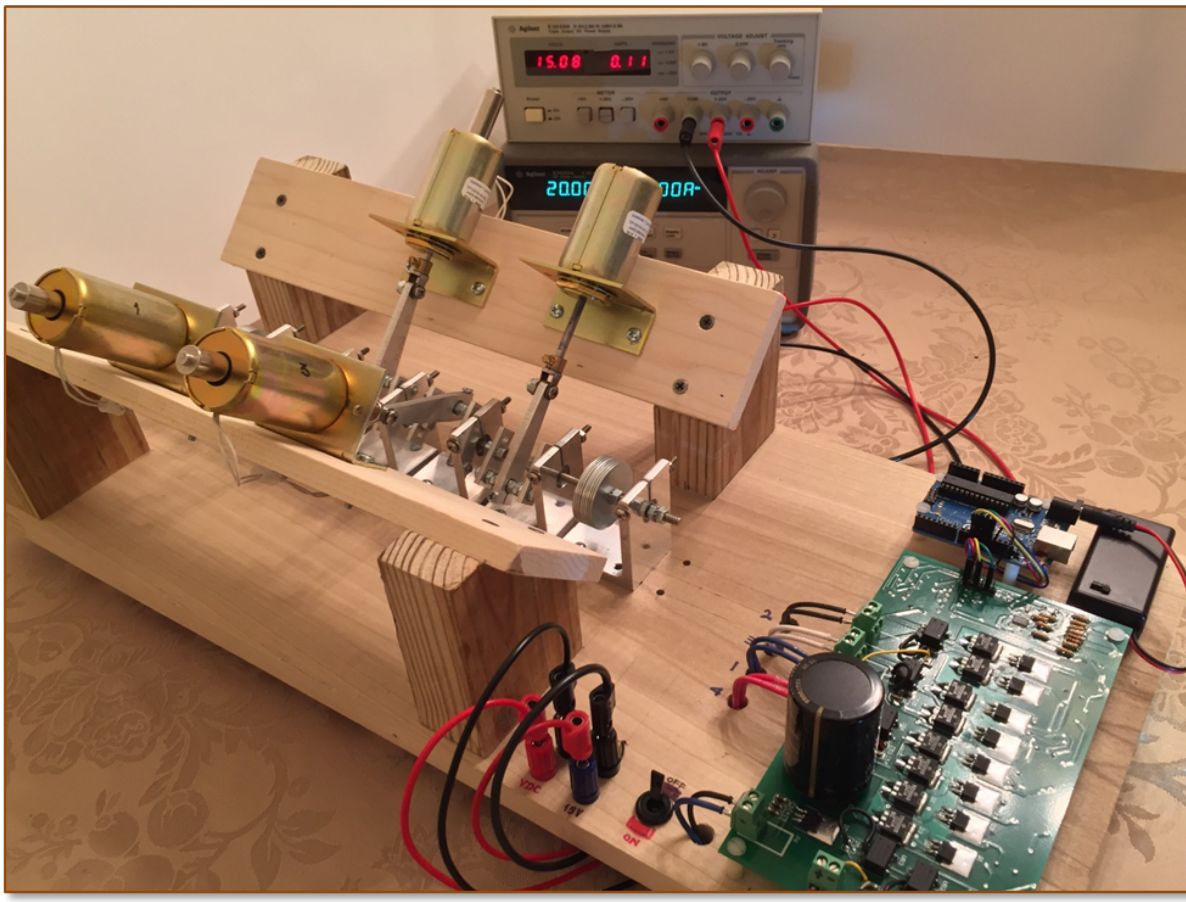


Figure 29: Complete setup of the V4 electric actuator (solenoid) engine

D. <u>Testing and Characterization</u>:

1. Characterize each actuator (solenoid) as described in the subsection, "Actuator Characterization" in this section on procedure.
2. Connect microcontroller, drive circuits, and the actuators as shown in Figures 27-29.
3. Check all connections of bolts, nuts, and screws in the assembly. Untightened, or improperly done attachments risk the safety of the assembly while running (final assembly shown in Figure 29).
4. Connect 15V power supply and 0-20V variable DC supply (VDC) to their respective terminals on the board.
5. Power up the microcontroller board using the battery pack, connect the USB plug and download the Arduino program from the PC. Prior to downloading, verify the program in Arduino IDE. The detailed program is given in the Appendix of this report.
6. Use pulse width modulation (PWM) to vary the on-time of the actuators for fixed off-time which was determined by the worst case time taken to de-energize an actuator (from the characterization data produced in step 1 above). The on-time variation changes the total period for one complete cycle of energizing and de-energizing over the four actuators and hence determines the time taken for one revolution. Measure the electric power supplied to the engine and its speed (RPM) over several trials as follows:
   - Create a small cardboard disc and fasten to the end of the crank shaft. This will serve as a guide to measuring RPM.
   - Mark a single position on the edge of the disc. This will be the reference for measuring rotations.
   - Utilize the slow motion camera on iPhone and capture video of this rotating disk over a 10s period. Count the number of revolutions in the captured video and compute the RPM by multiplying this count by 6 (since there six, 10s intervals in one minute).
7. Repeat engine characterization steps 2-6 by varying stroke length and using different engine configurations.

7. Graphs and Results

Characterization of Actuators

Tables 1-4 give characterization data for the four actuators (solenoids).

Start Position (mm)	Stroke Length (mm)	Minimum Supply Voltage (V volts)				Minimum Supplied Current (I mA)				Input Power (mW)	Solenoid Resistance R_L (Ω)	Start Position Inductance (mH)				Force (N)
		Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average			Trial 1	Trial 2	Trial 3	Average	
35	5	1.39	1.41	1.45	1.42	60	63	62	61.67	87.36	22.97	179.00	178.00	179.00	178.67	0.027
30	10	2.10	2.14	2.09	2.11	88	90	90	89.33	188.49	23.62	144.00	145.00	145.00	144.67	0.042
25	15	2.87	2.83	2.86	2.85	117	116	115	116.00	330.99	24.60	117.00	116.00	116.00	116.33	0.060
20	20	3.33	3.31	3.33	3.32	143	141	140	141.33	469.70	23.51	93.00	94.00	93.00	93.33	0.078
15	25	4.44	4.33	4.35	4.37	189	190	188	189.00	826.56	23.14	66.50	66.60	66.40	66.50	0.131
10	30	5.48	5.57	5.55	5.53	240	243	242	241.67	1337.22	22.90	57.80	57.80	57.90	57.83	0.187
5	35	7.59	7.46	7.83	7.63	331	330	331	330.67	2521.88	23.06	53.20	52.90	53.10	53.07	0.308

Table 1: Characterization of Solenoid 1

Start Position	Stroke Length	Supply Voltage (V volts)				Supplied Current (I mA)				Input Power	Solenoid Resistan	Start Position Inductance (mH)				Force (N)
		Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average			Trial 1	Trial 2	Trial 3	Average	
35	5	1.28	1.23	1.30	1.27	54	58	53	55.00	69.85	23.09	169.00	170.00	169.00	169.33	0.018
30	10	1.99	2.03	2.07	2.03	83	89	92	88.00	178.64	23.07	139.00	137.00	139.00	138.33	0.035
25	15	2.65	2.61	2.64	2.63	112	114	110	112.00	294.93	23.51	114.00	112.00	113.00	113.00	0.049
20	20	3.19	3.21	3.27	3.22	139	133	136	136.00	438.37	23.70	92.00	93.00	93.00	92.67	0.064
15	25	4.21	4.18	4.17	4.19	179	187	181	182.33	763.37	22.96	63.00	63.00	63.80	63.27	0.111
10	30	5.23	5.31	5.27	5.27	235	239	237	237.00	1248.99	22.24	50.70	51.40	50.80	50.97	0.168
5	35	7.41	7.36	7.61	7.46	327	322	329	326.00	2431.96	22.88	48.20	49.10	47.70	48.33	0.276

Table 2: Characterization of Solenoid 2

Start Position	Stroke Length	Supply Voltage (V volts)				Supplied Current (I mA)				Input Power	Solenoid Resistan	Start Position Inductance (mH)				Force (N)
		Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average			Trial 1	Trial 2	Trial 3	Average	
35	5	1.77	1.73	1.65	1.72	57	60	59	58.67	100.71	29.26	165.00	167.00	164.00	165.33	0.026
30	10	2.57	2.89	2.78	2.75	86	91	87	88.00	241.71	31.21	130.00	132.00	129.00	130.33	0.042
25	15	3.13	3.29	3.14	3.19	115	112	113	113.33	361.16	28.12	108.00	107.00	109.00	108.00	0.057
20	20	4.02	3.78	3.77	3.86	142	136	139	139.00	536.08	27.75	74.30	72.80	71.90	73.00	0.081
15	25	5.47	5.10	4.73	5.10	187	189	182	186.00	948.60	27.42	62.80	63.00	62.90	62.90	0.123
10	30	6.87	7.32	8.30	7.50	239	240	238	239.00	1791.70	31.37	55.40	55.30	55.40	55.37	0.176
5	35	9.88	8.74	10.82	9.81	329	327	325	327.00	3208.96	30.01	49.90	50.20	50.10	50.07	0.290

Table 3: Characterization of Solenoid 3

Start Position	Stroke Length	Supply Voltage (V volts)				Supplied Current (I mA)				Input Power	Solenoid Resistan	Start Position Inductance (mH)				Force (N)
		Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average			Trial 1	Trial 2	Trial 3	Average	
35	5	1.31	1.49	1.41	1.40	59	62	61	60.67	85.14	23.13	175.00	173.00	174.50	174.17	0.03
30	10	2.47	2.63	2.58	2.56	87	90	89	88.67	226.99	28.87	143.00	146.50	145.00	144.83	0.04
25	15	3.11	3.21	3.24	3.19	115	113	114	114.00	363.28	27.95	119.00	121.40	119.80	120.07	0.05
20	20	3.99	3.84	3.79	3.87	142	140	139	140.33	543.56	27.60	92.00	94.50	91.50	92.67	0.08
15	25	5.39	5.13	5.27	5.26	186	190	187	187.67	987.75	28.05	67.00	63.00	66.50	65.50	0.13
10	30	6.69	6.72	6.94	6.78	239	242	241	240.67	1632.52	28.19	55.50	53.80	55.50	54.93	0.18
5	35	9.78	9.81	9.83	9.81	331	329	329	329.67	3232.93	29.75	52.30	51.50	51.00	51.60	0.30

Table 4: Characterization of Solenoid 4

From the above tables it can be seen that there are some differences in the minimum current and power consumed by each actuator to produce necessary force to move its armature. These minor differences are due to variations in manufacturing. Figure 30 plots the minimum current required and force produced for different stroke lengths of solenoid 1.

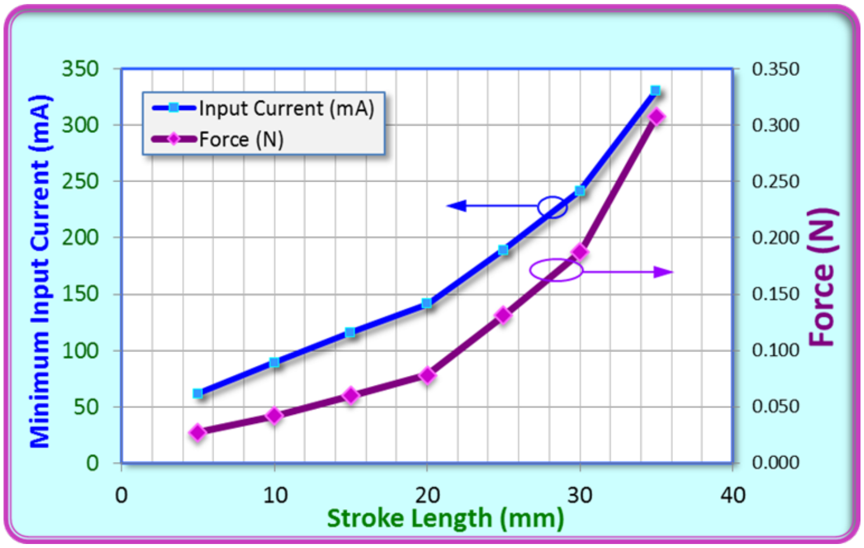


Figure 30: Minimum current required and force produced by single solenoid

Figure 31 shows waveform for current flowing through a solenoid when it is energized and the current reaches its maximum value and when it is de-energized when the current goes back to zero. The figure depicts two waveforms: green one employs single switch and one freewheeling diode (Figure 7), and blue waveform for the technique using asymmetric full-bridge (Figure 8). It can be clearly seen that the de-energizing time is much shorter with asymmetric full-bridge driving circuit, which will result in a faster engine speed.

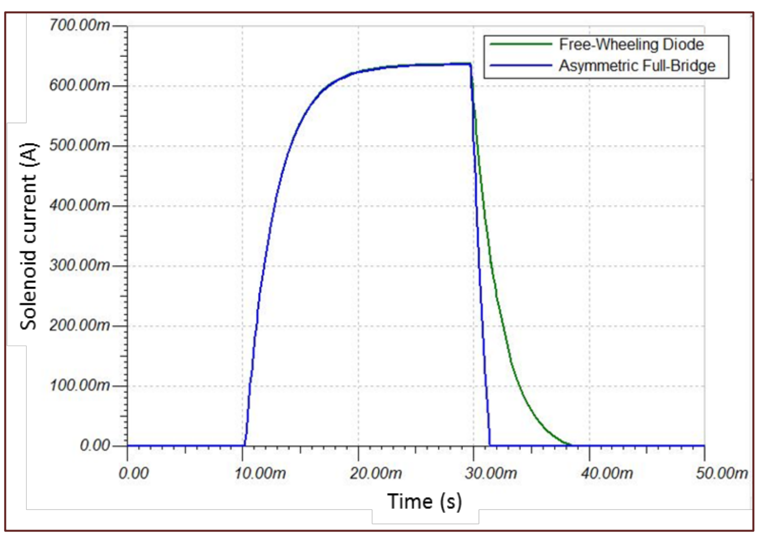


Figure 31: Current waveforms for energizing / de-energizing one solenoid

Tables 5 and 6 give results for torque produced by one actuator for stroke lengths of 1.5cm and 3cm. Different stroke lengths can be achieved by attaching the connecting rod to the two holes on either side of the central hole on the crankshaft torque arm shown in Figure 14 (Figure 15 shows the attachment for stroke length of 3cm). For a single actuator, torque produced in N·cm for different current values for the two stroke lengths is as shown in Figure 32.

Supply Voltage	Supplied Current (I mA) Trial 1	Trial 2	Trial 3	Average	Input Power (mW)	Force (N)	Torque (N·cm)
8	349	347	348	348.00	2784.00	0.541	0.406
10	436	433	435	434.67	4346.67	0.844	0.633
12	522	523	521	522.00	6264.00	1.217	0.913
14	609	608	607	608.00	8512.00	1.651	1.238
16	692	691	690	691.00	11056.00	2.133	1.600
18	775	776	772	774.33	13938.00	2.678	2.009
20	856	854	852	854.00	17080.00	3.258	2.443

Table 5: Toque for 1.5cm stroke

Supply Voltage	Supplied Current (I mA) Trial 1	Trial 2	Trial 3	Average	Input Power (mW)	Force (N)	Torque (N·cm)
8	365	364	362	363.67	2909.33	0.425	0.638
10	454	453	450	452.33	4523.33	0.658	0.987
12	542	541	539	540.67	6488.00	0.940	1.410
14	629	627	628	628.00	8792.00	1.269	1.903
16	706	708	710	708.00	11328.00	1.612	2.419
18	791	788	785	788.00	14184.00	1.997	2.996
20	862	860	857	859.67	17193.33	2.377	3.566

Table 6: Toque for 3cm stroke

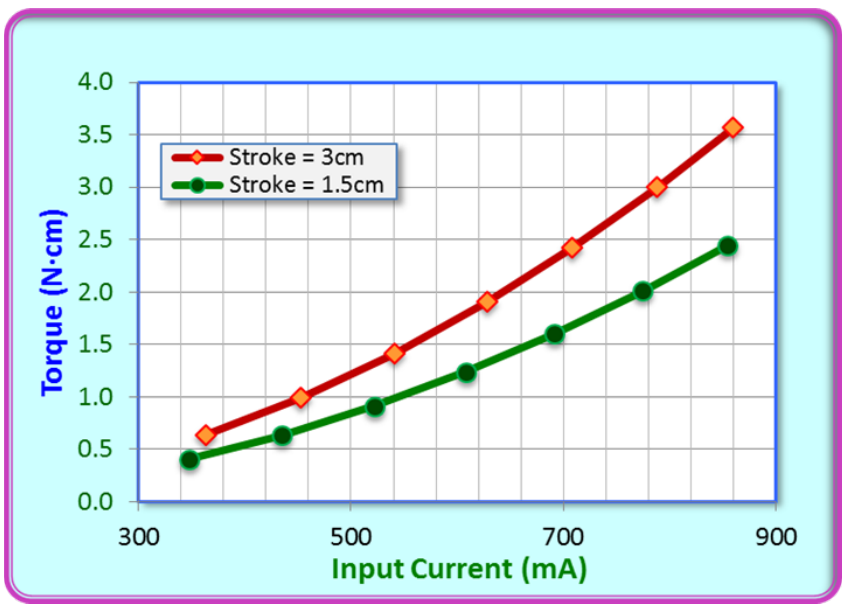


Figure 32: Torque produced by a single solenoid

Microcontroller Output

Based on the specified actuator energizing time (on-time, t_{on}) and de-energizing time (off-time, t_{off}), the Arduino program generates low voltage control signals. These signals determine the energizing (firing) order and period for one complete cycle for the four actuators. Figure 33 shows the waveforms captured at the output signal terminals of the microcontroller while being connected to the driving circuit board. It shows the 1-4-3-2 firing order for the four-actuator engine.

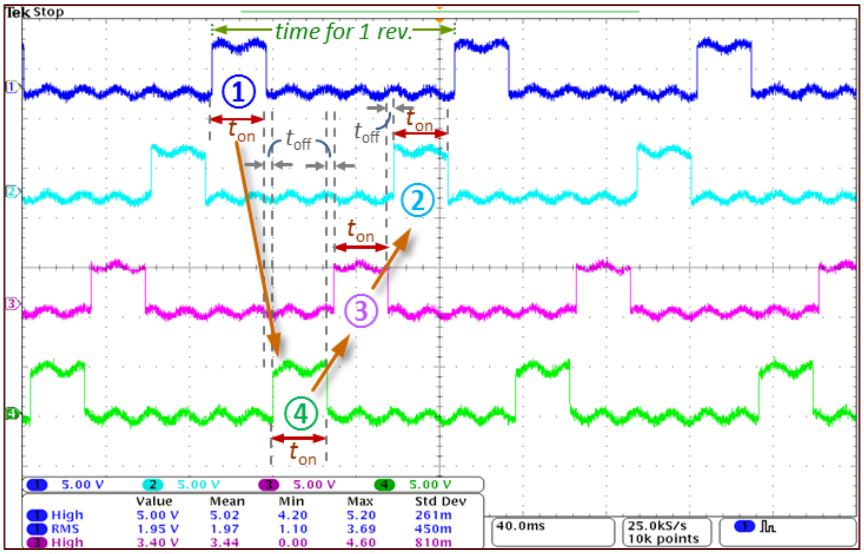


Figure 33: Control signals at the output of the microcontroller

Actuator Signals

Figure 34 depicts voltage waveforms across each of the four actuators. These waveforms correspond to voltage waveforms across an inductor when it is charged and discharged. Detailed current and voltage waveforms depicting energizing (charging) and de-energizing (discharging) of two actuators are shown in Figure 35.

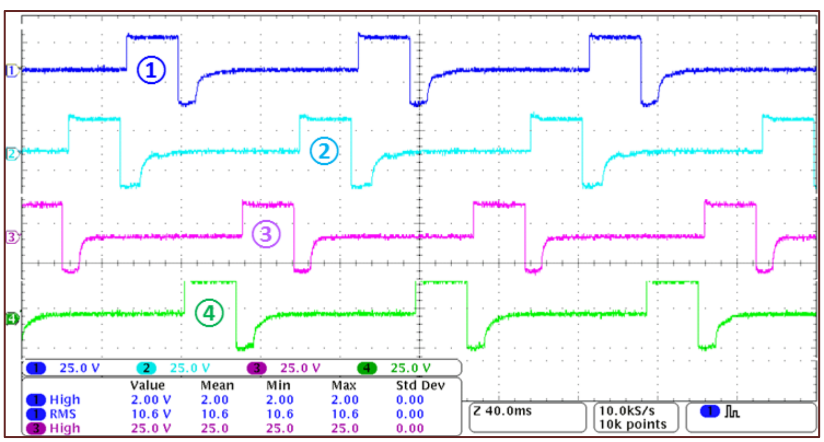


Figure 34: Voltage waveforms across four actuators

For an ideal inductor when it is fully charged, the voltage across it is zero. However, real inductors have parasitic resistance which results in a non-zero voltage drop. In addition to this voltage, there will be voltage drop across two MOSFET switches in series with an actuator inductance in the asymmetric half-bridge. This non-zero voltage drop after being fully charged can be seen in Figures 34 and 35. During discharge since the inductor current cannot be interrupted instantaneously, it continues to flow in the same direction, discharging through the two freewheeling diodes. This implies that the polarity of voltage across the actuator inductance is reversed during the de-energizing period.

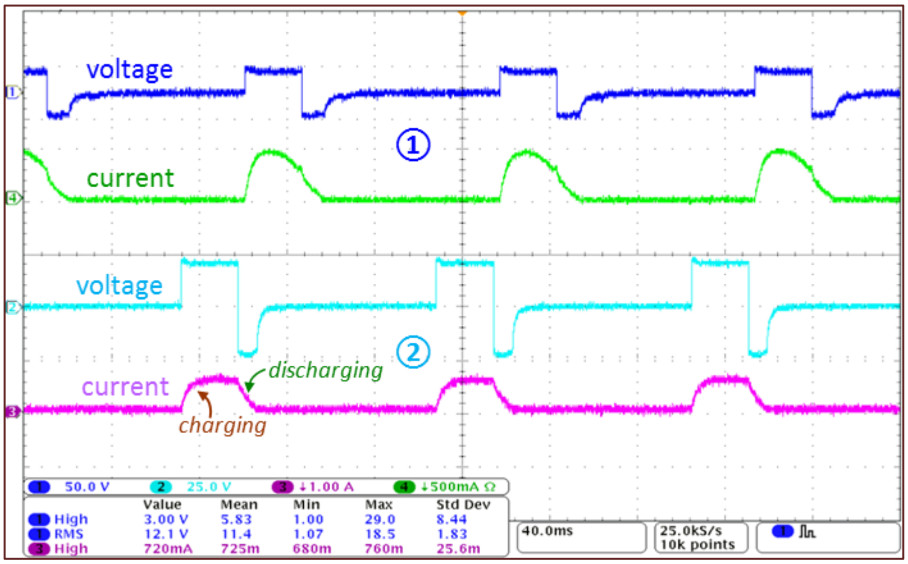


Figure 35: Current and Voltage waveform details for two actuators

V4 (V angle of 90°) Actuator Engine (stroke length = 3cm)

Results demonstrating the operation of a V4 electric actuator engine for stroke length of 3cm are given in Table 7. These results are plotted and shown in Figure 36. It clearly demonstrates control of engine speed by varying on-time, t_{on} and keeping supply voltage (VDC) fixed. Speed varies considerably for t_{on} reduction up to about 200ms, after which the on-time becomes so long that the engine slows down to almost constant slow speed and may eventually stall. Low values of VDC need longer on-times to run the engine resulting in relatively slower speeds.

Power supplied to the V4 engine for varying t_{on} is shown in Figure 37. For large values of on-time actuators remain on for most of the time period resulting in almost constant current for a fixed VDC. Once an inductor is fully charged, the current remains at its maximum value regardless of how long it is kept energized.

An alternate way to vary engine speed is by varying the supply voltage VDC for fixed on-time. This data is presented in Table 8 and plotted in Figure 38 for 3cm stroke length.

VDC = 20V

t_on (ms)	RPM Trial 1	RPM Trial 2	RPM Trial 3	RPM Average	Current I (mA) Trial 1	Current I (mA) Trial 2	Current I (mA) Trial 3	Current I (mA) Average	Input Power (mW)
20									
25	574	567	570	570	300	306	309	305	6.10
30	497	516	509	507	375	363	357	365	7.30
35	438	430	437	435	397	390	392	393	7.86
40	390	391	380	387	433	420	428	427	8.54
45	320	335	331	329	502	493	499	498	9.96
50	267	273	275	272	578	565	561	568	11.36
70	218	192	220	210	752	740	743	745	14.90
90	193	162	185	180	797	807	796	800	16.00
100	172	168	169	170	809	818	809	812	16.24
150	101	105	109	105	823	812	819	818	16.36
200	74	73	83	77	811	829	820	820	16.40
250	58	59	68	62	837	829	824	830	16.60
300	48	48	57	51	832	838	835	835	16.70
350	37	56	42	45	847	846	860	851	17.02
400	40	53	38	44	854	860	857	857	17.14
450	29	42	33	35	868	859	865	864	17.28
500	33	26	40	33	873	879	858	870	17.40

VDC = 16V

t_on (ms)	RPM Trial 1	RPM Trial 2	RPM Trial 3	RPM Average	Current I (mA) Trial 1	Current I (mA) Trial 2	Current I (mA) Trial 3	Current I (mA) Average	Input Power (mW)
20									
25									
30									
35	366	370	380	372	280	289	286	285	4.56
40	276	298	331	302	367	351	353	357	5.71
45	217	249	263	243	391	380	387	386	6.18
50	224	218	220	221	431	439	441	437	6.99
70	162	143	132	146	501	517	512	510	8.16
90	95	119	101	105	559	572	573	568	9.09
100	92	101	109	101	591	602	595	596	9.54
150	83	63	70	72	618	611	613	614	9.82
200	68	58	54	60	620	621	622	621	9.94
250	39	42	45	42	656	643	645	648	10.37
300	33	37	38	36	658	660	671	663	10.61
350	23	37	35	32	679	680	666	675	10.80
400	33	29	28	30	679	683	684	682	10.91
450	29	22	30	27	694	691	685	690	11.04
500	18	29	30	26	701	699	691	697	11.15

VDC = 12V

t_on (ms)	RPM Trial 1	RPM Trial 2	RPM Trial 3	RPM Average	Current I (mA) Trial 1	Current I (mA) Trial 2	Current I (mA) Trial 3	Current I (mA) Average	Input Power (mW)
20									
25									
30									
35									
40									
45									
50									
70									
90	90	80	78	83	300	295	299	298	3.58
100	69	81	75	75	338	347	341	342	4.10
150	63	49	59	57	401	397	396	398	4.78
200	49	40	42	44	410	400	411	407	4.88
250	29	35	40	35	419	433	426	426	5.11
300	31	24	35	30	460	466	469	465	5.58
350	23	33	30	29	479	478	471	476	5.71
400	20	29	23	24	491	490	486	489	5.87
450	24	20	19	21	503	520	516	513	6.16
500	18	17	24	20	511	517	520	516	6.19

Table 7: Characterization data for V4 electric actuator engine

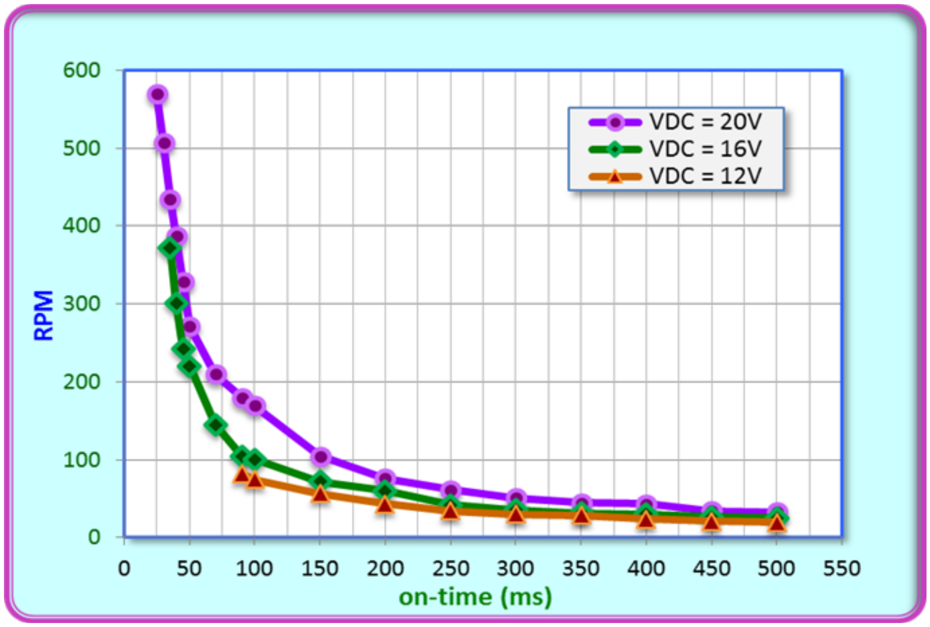


Figure 36: Effect of t_{on} on V4 (3cm stroke) engine speed (RPM)

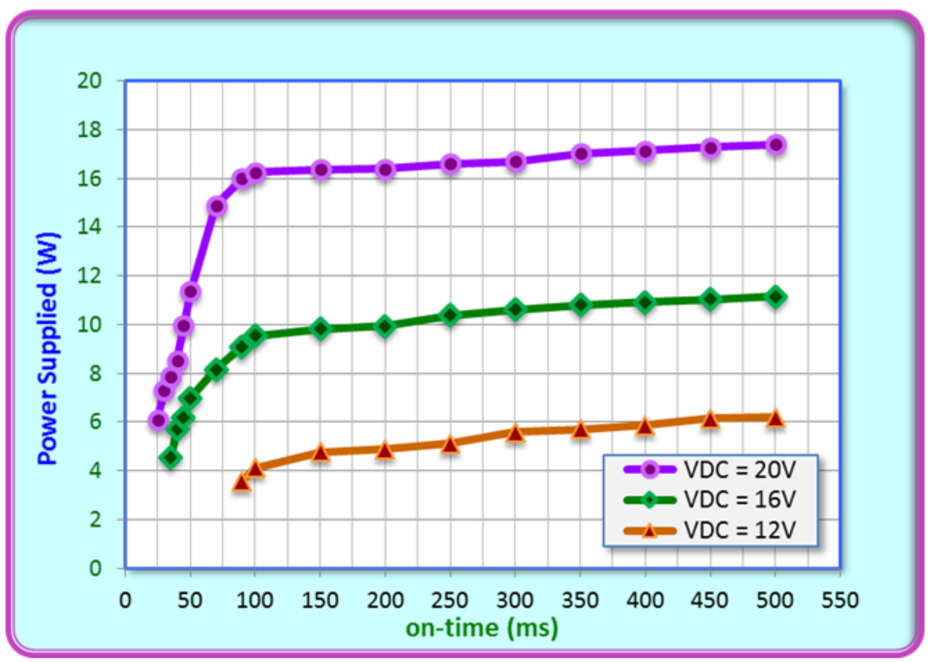


Figure 37: Power Supplied to V4 (3cm stroke) engine for different t_{on} values

VDC (Volts)	t_on = 40ms				t_on = 50ms				t_on = 100ms			
	RPM				RPM				RPM			
	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
12									69	78	69	72
13									79	86	83	83
14									102	94	92	96
15					199	207	193	200	96	99	98	98
16	321	305	301	309	210	224	228	221	109	101	105	105
17	319	321	337	326	239	245	223	236	108	121	113	114
18	363	349	350	354	265	253	252	257	143	141	130	138
19	371	393	375	380	277	281	243	267	161	154	149	155
20	387	397	386	390	288	261	288	279	154	159	182	165

Table 8: Varying speed by varying voltage VDC for fixed t_{on} (3cm stroke)

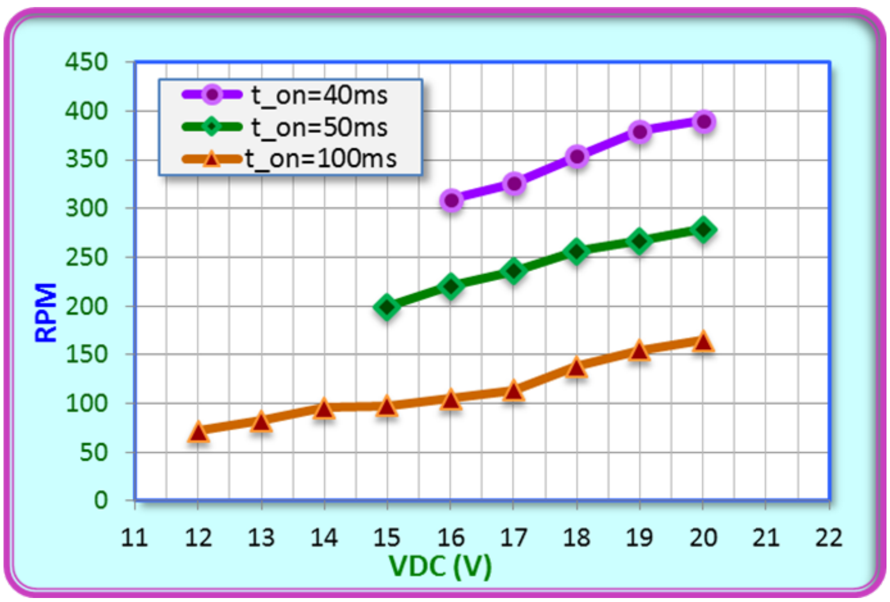


Figure 38: Effect of supply voltage VDC on V4 speed for fixed t_{on} (3cm stroke)

V4 (V angle of 90°) Actuator Engine (stroke length = 1.5cm)

Results demonstrating the operation of a V4 electric actuator engine for stroke length of 1.5 cm are given in Table 9. These results are plotted and shown in Figure 39. Since the results obtained for 3cm stroke length engine indicated that there is limited speed variation due to supply voltage changes, this engine was characterized by keeping VDC fixed at its highest value of 20V which results in maximum speed for the design system. Plots in Figure 39 demonstrate control of engine speed by varying on-time, t_{on} and keeping supply voltage (VDC) fixed. Plots also show the power supplied to the engine.

t_on (ms)	VDC = 20V								
	RPM				Current I (mA)				Input Power
	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	
20									
25	559	545	543	549	284	293	300	292	5.85
30	484	501	491	492	339	351	372	354	7.08
35	393	375	371	380	381	387	363	377	7.54
40	329	333	346	336	397	409	400	402	8.04
45	268	278	264	270	480	468	474	474	9.48
50	220	211	199	210	571	560	552	561	11.22
70	178	163	154	165	617	623	617	619	12.38
90	145	139	142	142	701	689	689	693	13.86
100	117	129	126	124	741	747	723	737	14.74
150	91	103	99	98	776	793	798	789	15.78
200	89	92	98	93	819	801	813	811	16.22
250	77	73	66	72	823	815	816	818	16.36
300	74	62	67	68	837	834	819	830	16.60
350	47	51	64	54	855	851	841	849	16.98
400	43	50	65	53	857	861	838	852	17.04
450	40	51	53	48	848	856	861	855	17.10
500	39	52	44	45	867	873	864	868	17.36

Table 9: Characterization data for V4 engine (1.5cm stroke, VDC=20V)

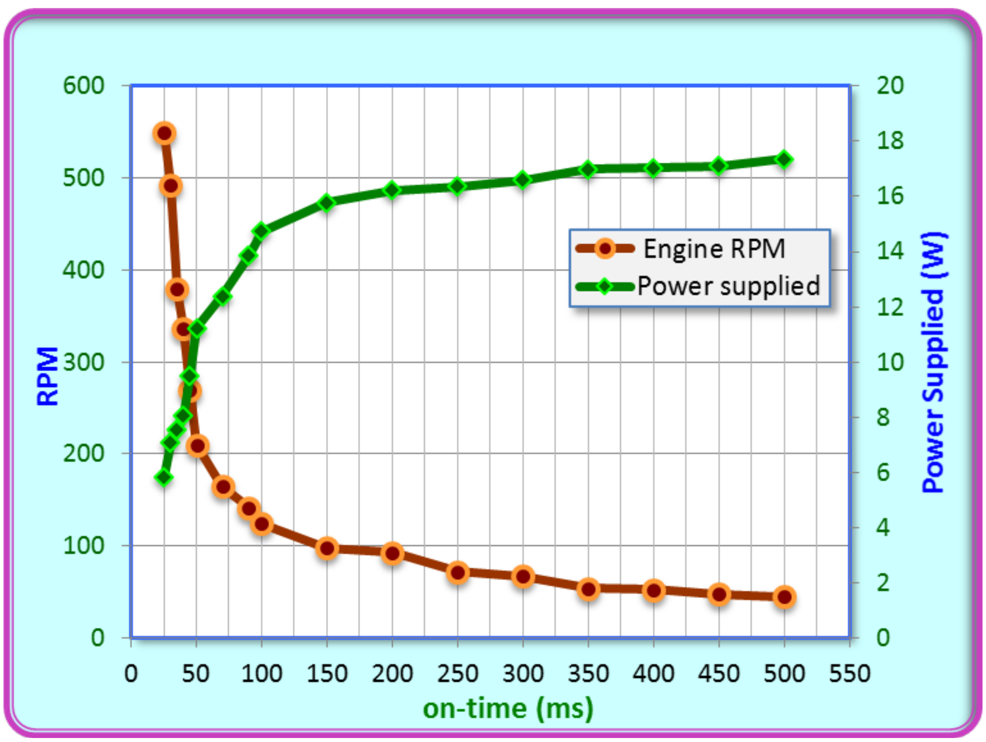


Figure 39: Speed and power supplied for V4 engine (1.5cm stroke, VDC=20V)

Boxer (V angle of 180°) Actuator Engine (stroke lengths = 3cm and 1.5cm)

Results demonstrating the operation of a Boxer electric actuator engine for stroke lengths of 3 cm and 1.5 cm are given in Tables 10 and 11, respectively. These results are plotted and shown in Figures 40 and 41. A Boxer engine has its actuators placed flat on the base (i.e., V angle of 180°). Since the opposite pistons (armatures) go back and forth like two boxers exchanging punches, it is called "Boxer" engine.

t_on (ms)	VDC = 20V								
	RPM				Current I (mA)				Input Power
	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	
20									
25	583	589	565	579	114	110	97	107	2.14
30	500	520	519	513	131	123	133	129	2.58
35	460	471	446	459	133	128	132	131	2.62
40	400	403	381	395	135	137	127	133	2.66
45	375	380	357	371	140	147	136	141	2.82
50	355	350	335	347	143	139	153	145	2.90
70	317	301	314	311	148	150	155	151	3.02
90	291	267	279	279	170	162	172	168	3.36
100	232	229	214	225	184	177	176	179	3.58
150	184	179	177	180	183	189	192	188	3.76
200	161	163	149	158	199	204	203	202	4.04
250	133	145	132	137	212	200	215	209	4.18
300	119	124	122	122	220	215	228	221	4.42
350	99	110	84	98	223	227	222	224	4.48
400	62	75	52	63	237	232	224	231	4.62
450	39	47	40	42	242	240	229	237	4.74
500	37	41	35	38	255	249	240	248	4.96

Table 10: Characterization data for Boxer engine (3cm stroke, VDC=20V)

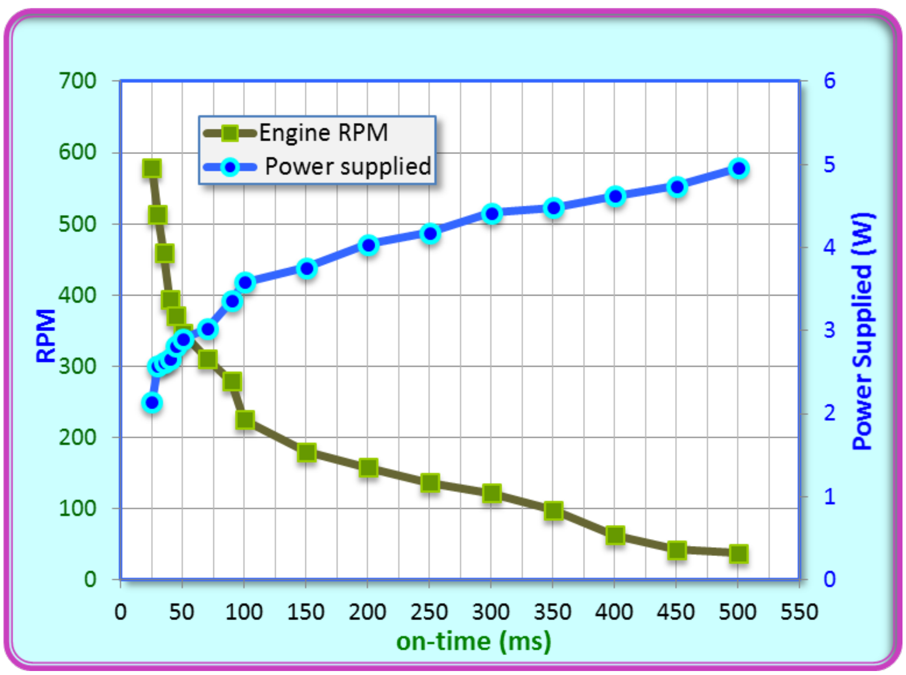


Figure 40: Speed and power supplied for Boxer engine (3cm stroke, VDC=20V)

t_on (ms)	VDC = 20V								
	RPM				Current I (mA)				Input Power
	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	
20									
25	564	560	549	558	202	182	195	193	3.86
30	470	461	460	464	218	213	211	214	4.28
35	397	391	373	387	214	215	219	216	4.32
40	336	351	353	347	220	219	212	217	4.34
45	305	323	313	314	225	220	221	222	4.44
50	291	280	280	284	234	227	232	231	4.62
70	229	241	228	233	234	229	236	233	4.66
90	179	186	166	177	239	236	230	235	4.70
100	158	153	139	150	241	235	241	239	4.78
150	104	117	108	110	241	247	247	245	4.90
200	70	79	76	75	245	251	248	248	4.96
250	58	64	54	59	257	254	245	252	5.04
300	44	50	59	51	258	255	252	255	5.10
350	51	49	44	48	261	259	251	257	5.14
400	47	40	44	44	271	277	262	270	5.40
450	41	38	38	39	278	280	255	271	5.42
500	29	40	39	36	281	278	266	275	5.50

Table 11: Characterization data for Boxer engine (1.5cm stroke, VDC=20V)

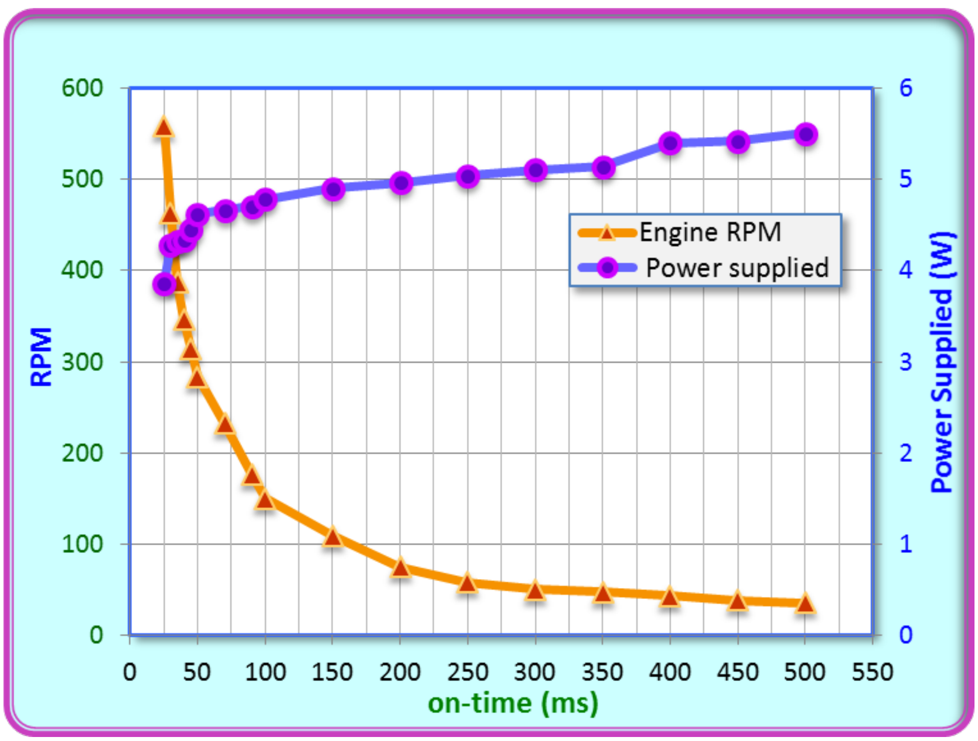


Figure 41: Speed and power supplied for Boxer engine (1.5cm stroke, VDC=20V)

Comparison of Various Actuator Engines

Results from Tables 7, 9-11 were extracted and are compiled in Table 12 in order to compare engine speed performance of different electric linear actuator engine configurations. These comparisons are depicted graphically in Figures 42 and 43.

t_on (ms)	V4 (15mm)		V4 (30mm)		Boxer (15mm)		Boxer (30mm)	
	RPM	Power (W)	RPM	Power (W)	RPM	Power (W)	RPM	Power (W)
20								
25	549	5.84	570	6.10	558	3.86	579	2.14
30	492	7.08	507	7.30	464	4.28	513	2.58
35	380	7.54	435	7.86	387	4.32	459	2.62
40	336	8.04	387	8.54	347	4.34	395	2.66
45	270	9.48	329	9.96	314	4.44	371	2.82
50	210	11.22	272	11.36	284	4.62	347	2.90
70	165	12.38	210	14.90	233	4.66	311	3.02
90	142	13.86	180	16.00	177	4.70	279	3.36
100	124	14.74	170	16.24	150	4.78	225	3.58
150	98	15.78	105	16.36	110	4.90	180	3.76
200	93	16.22	77	16.40	75	4.96	158	4.04
250	72	16.36	62	16.60	59	5.04	137	4.18
300	68	16.60	51	16.70	51	5.10	122	4.42
350	54	16.98	45	17.02	48	5.14	98	4.48
400	53	17.04	44	17.14	44	5.40	63	4.62
450	48	17.10	35	17.28	39	5.42	42	4.74
500	45	17.36	33	17.40	36	5.50	38	4.96

Table 12: Comparison of different linear actuator engines (VDC=20V)

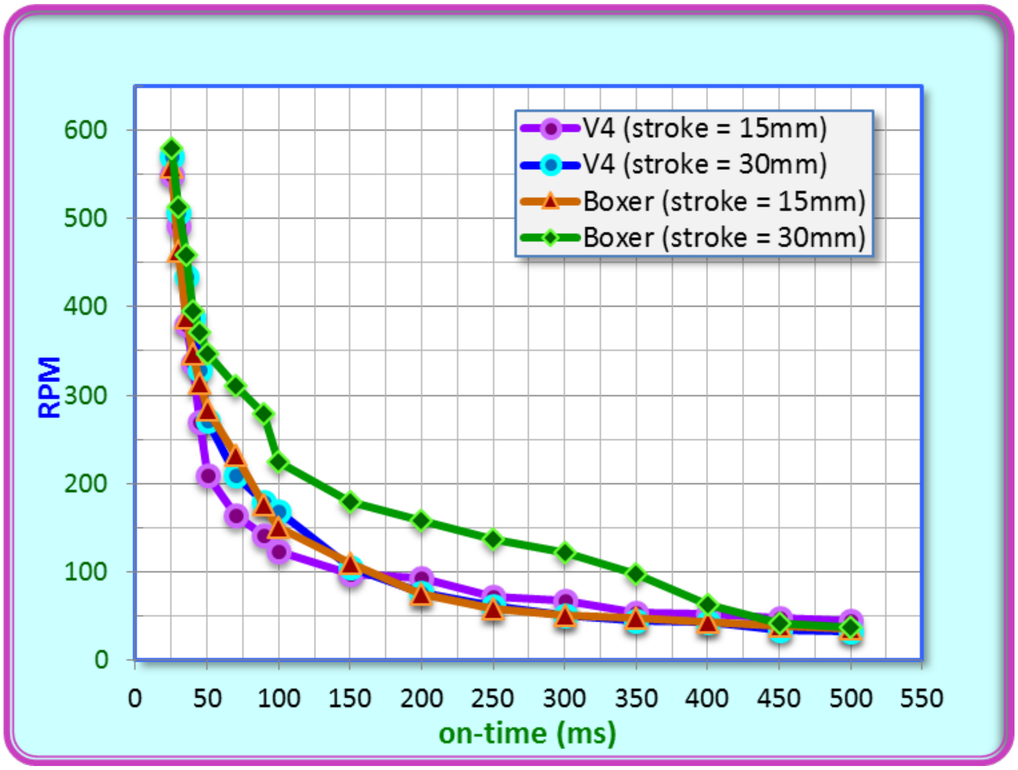


Figure 42: Comparing speeds of different actuator engines (VDC=20V)

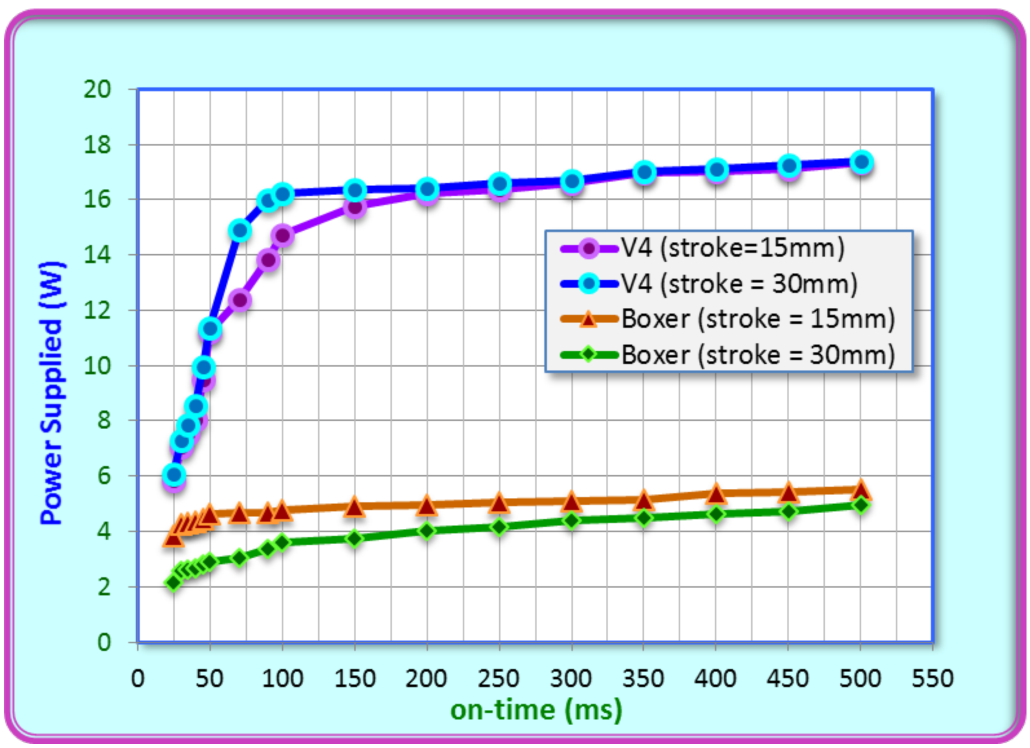


Figure 43: Comparing power supplied for different actuator engines (VDC=20V)

9. Conclusions

The goal of this engineering project was to design and implement a 4-cylinder equivalent for the electric component of a hybrid engine that functions just like a conventional ICE. The electric engine was implemented using four actuators which provided reciprocating motion similar to the ICE pistons. This enables the proposed actuator based electric engine to be connected to the same crankshaft on which ICE pistons are connected resulting in an integrated “true” HEV. The proposed integrated engine eliminates the need for a mechanical coupling mechanism as in conventional parallel HEV or the need for separate generator-motor combination as in conventional series HEV. The electric drive can be energized as needed based on different demands put on the car, e.g. for during acceleration, going up-hill, etc. Furthermore, this true-HEV also eliminates the need for a separate starter motor to crank the IC engine.

Several preliminary designs using one and two actuators were done in order to study the behavior of actuators in terms of force produced, time for energizing and de-energizing, power requirements, crankshaft design, etc. Based on these early designs, final scaled version of 4-actuator electric engine was designed and implemented. As shown in Figures 21-22 two actuator (cylinder) configurations - V4 and Boxer were successfully implemented and characterized for two stroke lengths of 1.5cm and 3cm. These actuators were controlled using asymmetric full-bridge circuit which was controlled by pulse width modulated pulse trains provided by the Arduino UNO microcontroller. As seen in Figure 31, asymmetric full-bridge resulted in a faster de-energizing (turn-off) time for an actuator compared to the circuit with one switch and one free-wheeling diode. For 4-actuator engine, this results in a shorter idle time for an actuator, yielding a shorter overall time period for one revolution and hence increased speed of the engine. Keeping the turn-off time fixed at the minimum value required, engine speed was varied by modulating the turn-on time.

Based on the tests and characterization data presented in section 8, the electric engine for a True-HEV was successfully designed and demonstrated for all engine configurations and stroke lengths. Based on the overall data plotted in Figure 42, an overall speed variation of 579 RPM to as low as 33 RPM was achieved by varying the on-time of actuators. As seen in Figure 38, attempt to vary engine speed by varying supply voltage (VDC) did not result in a similar range of speed. Furthermore, in reality it is costlier to create a power supply to have varying output voltage compared to one with a fixed value. In all subsequent tests, VDC was fixed at 20V since that value resulted in highest speed. From Figure 38, it can be seen that as on-time is increased from around 20ms to about 200ms there is a reasonable proportionate decrease in the engine speed. Further increase in the on-time does not result in similar reduction in speed. Total time for one revolution in the proposed engine configuration is determined by the total time for energizing and de-energizing four actuators as shown in Figures 33-35. For a fixed turn-off time, time for one revolution is changed by varying on-time. When the on-time increased to a large value beyond what is needed for the actuator to energize to its maximum value, it just sits idle and does not result in reduced speed. As on-time increases, power supplied to the actuators is also proportionately increased. Beyond the maximum power needed[1], an actuator does not draw any more and hence for very large on-times the power supplied remains almost constant. Maximum speed of 579 RPM was achieved for the 2-stroke scaled Boxer engine with stoke length of 3cm. In general, over the entire on-time variation range the Boxer engine ran somewhat faster than other configurations, and needed much lower supplied power (see Figures 42-43). In a Boxer engine the actuators are placed flat instead of at an angle in a V4 resulting in a lower resistive force provided by other de-energized actuator armatures to the energized one resulting in better performance. Maximum torque of 3.57 Ncm was produced at 860 mA (VDC of 20V) with stroke length of 3cm for a 2-stroke engine with single actuator energizing (firing) at a given time (see Table 6). If more torque is needed, the microcontroller program can be changed to fire two actuators at a time as needed. Footprint of a V4 engine is smaller than Boxer but it is taller. Shorter height of the Boxer engine results in lower center of gravity and hence it has lesser engine vibrations compared to V4 engine.

The proposed actuator engine for a True-HEV, based on the results presented here, provides an innovation for existing hybrid vehicles. The control is simple and flexible and the engine can be easily run as a 2-stroke, 4-stroke, or even 1-stroke (with bidirectional actuators). Lastly, electric actuators run cleaner without any gaseous emissions than the pistons in the ICE.

10. Impact of the Project

- **"True" Hybrid Engine System:**
  - Electrically energized linear actuators can be used to create an engine similar to the gasoline powered internal combustion engine (ICE) used in automobiles.
  - Electrical engine actuators presented here can be integrated with ICE pistons in a single engine chassis using a common crankshaft thus creating a "true" integrated hybrid engine without any complex coupling mechanism as is done in conventional hybrid vehicles.

[1] Maximum current drawn = *VDC*/*R*, where *R* is the total resistance of the energizing circuit which includes resistances of the actuator coils and the switches. Power supplied is maximum current × *VDC*

- The proposed True-HEV can be built by simply replacing few cylinders in an IC engine with linear actuators and modifying the electronic ignition system! This results in a cheaper HEV compared to existing HEVs.
- Two components of this hybrid engine can be driven by a single electronic drive or ignition system which is modified to handle this “true” hybrid engine. This electronic system can then be controlled by a master microcontroller.
- Linear actuators and ICE pistons can work together or on their own in different ways depending on the engine power needs resulting in flexibility of control.
- The engine can also be run as a one-stroke (with bidirectional solenoids), two-stroke, or four-stroke engine as needed in each application.

- **Fuel Emissions:**

  There are four types of particles emitted from an ICE: Hydrocarbons, carbon monoxide, solid particles, and oxides of nitrogen. Electric linear actuators do not emit these harmful products; therefore, an electric or hybrid engine is a cleaner alternative.

11. Further Work and Future Applications

- **Implementation:**
  - Explore other electric actuators like linear switched reluctance motors which are resilient to high temperature operations
  - Design, implement, and characterize electric actuators based on the torque and speed specifications of IC engines from existing hybrid electric vehicles.
  - Implement feedback control mechanism with speed sensors to regulate engine speed

- **Proposed True-HEV Design 1**: ***Integrated Hybrid Engine***

  In an existing IC engine replace few cylinders by appropriately scaled electric actuators as shown in the Figure 44 where 2 cylinders of a V4 engine are replaced by 2 actuators. Electric actuators and ICE pistons in this engine are connected to the same crankshaft resulting in a truly integrated hybrid electric engine. For this integrated engine a single microcontroller can be used to fire sparkplugs and energize actuators in a correct sequence to achieve smooth rotary motion of the crankshaft. Because of the electrically energized actuators there is no need for an external starter motor to crank the ICE pistons.

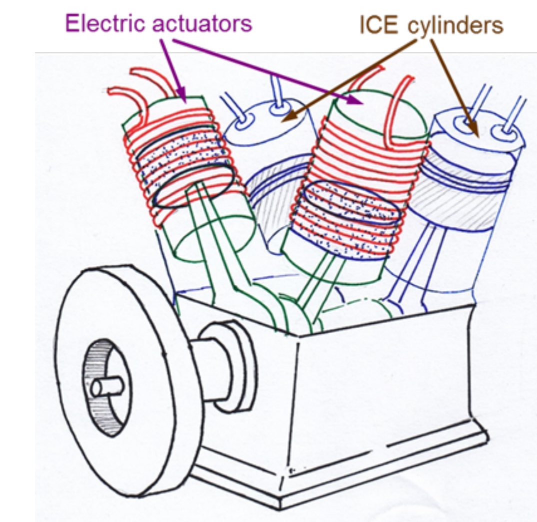


Figure 44: True-HEV Design 1 – *Integrated* V4 Engine

- **Proposed True-HEV Design 2**: ***Integrated Hybrid Cylinder***

  Alternatively, electric actuator can be integrated with the ICE cylinder as shown in Figure 45. A ferromagnetic armature is added to the piston and the stator with its coil can be placed at the end of the cylinder. When the stator coil is energized at the right moment, it pulls in the armature adding to the mechanical force produced by the ICE. This electrical component also does not need external coupling or gearbox mechanism. When the actuator is not used for motoring, it can also operate in the generating mode to convert mechanical energy of the ICE to electrical energy. Electrical actuation also eliminates the need for a starter motor.

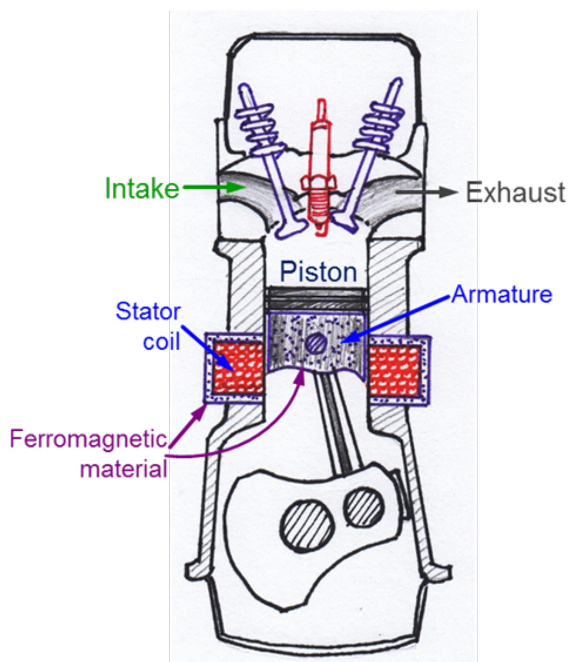


Figure 45: True-HEV Design 2 – *Integrated* Hybrid Cylinder

12. Possible Errors

- At the start of the design process actuators (solenoids) were characterized for their inductance at given stroke lengths:
  - The characterization revealed that some solenoids varied minimally in characteristics.
  - This minute difference could have led to fluctuations in the speed of the running engine.
- A lack of a tachometer meant that the device had to be characterized using an innovative system which may not have always provided the most accurate reading:
  - This system called for the use of a slow motion camera to count the number of times a black mark passed a given point on a white disc. Afterwards, the number of revolutions over a ten second period was multiplied by a factor of six to find the RPM.
  - Whereas resources were not previously present, this issue can now be fixed with a Hall-effect sensor for more accurate readings.
- All parts could not be constructed with machines, thus slight misalignment of parts, due to human error, could lead to minor fluctuations.

13. Acknowledgements

We would like to thank Devendra Patil at the Renewable Energy and Vehicular Technology Lab at UT Dallas for his assistance in teaching us about solenoids and underlying circuit components. His help in manually fixing the circuit board layout is highly appreciated. Our sincere thanks to Dr. Fahimi at UT Dallas for his help in explaining the theory, improving the ideas, and critiquing our project. Thanks to Feroze Sidhwa of Precise Circuits and Mark Powell of the UT Dallas machine shop for assisting in cutting metal parts with their precision tools. Last but not the least we appreciate all the support and encouragement at every step provided by our parents.

14. Annotated Bibliography

Bicron (2015): "*Solenoid Design and Operation*." *Bicron Electronics Company*. 25 Sept. 2015
[Web] http://www.sal.wisc.edu/PFIS/docs/rss-vis/archive/public/Product Manuals/bicron/soldesop.pdf
This article explains in detail about linear actuators, or solenoids. It goes through major points such as magnetic efficiency, performance, and construction. This information will work towards selection of the solenoid, and testing the performance of the final outcome.

Britannica-2 (2015): *Two-stroke cycle*.
[Web] http:// http://www.britannica.com/technology/two-stroke-cycle
This online source gives an illustration of a two-stroke engine.

Britannica-4 (2015): *Four-stroke engine Illustration*.
[Web] http://media.web.britannica.com/eb-media/72/93572-034-28C16785.jpg
This online source gives an illustration of a four-stroke engine.

Car and Driver (2011): "*The Physics Of: Engine Cylinder-Bank Angles - Feature*." *The Physics of Engine Cylinder-Bank Angles*. 16 Sept. 2015. [Web] http://www.caranddriver.com/features/the-physics-of-engine-cylinder-bank-angles-feature.
This article explains the reasoning and functioning of a "V-Shaped" internal combustion engine. It explains the mechanics behind the using this engine form. It gives information about the degree of the engine correlated to its performance. The article provides ideas for the mechanical design of the engine in the project.

C. Mi, M. A. Mansur, D. Gao (2011): "*Hybrid Electric Vehicles: Principles and Applications with Practical Perspectives,*" John Wiley, 2011.
This book gives an overview of hybrid engines and different components of hybrid electric vehicles.

Durfee, W. (2011): "*Arduino Microcontroller Guide*." Ver. Oct-2011 (2011).
This journal gives insight on the microcontroller Arduino. It gives general coding syntax, and capabilities of an Arduino microcontroller board. The controlling of the gate drive in the project will be done using Arduino as well, thus will be useful in the project.

K. Nice, J. Layton (2015): "*How Hybrid Cars Work",* Sept 2015
[Web] http://auto.howstuffworks.com/hybrid-car7.htm
This article gives animated illustration of a hybrid engine.

Mitchell, Colin (2014): "*Transistor Circuits (pt. 2*)." Talking Electronics, 14 July 2014.
[Web] http://www.talkingelectronics.com/projects/200TrCcts/101-200TransistorCircuits.pdf
General information regarding circuitry and identification of certain parts and their respective uses are outlined in this ebook. It provides valuable and miscellaneous

knowledge and assists in making appropriate decisions to acquire a desired outcome for the project.

Nmosfet (2013) "*STP310N10F7: N-channel Power MOSFET in a TO-220 package*" (2013).
[Web]http://www.st.com/web/en/resource/technical/document/datasheet/DM00039392.pdf
This data sheet gives information about a Power MOSFET (STP310N10F7), mostly the technicalities. Electrical characteristics, test circuits are two of the major aspects it covers. This MOSFET will be used in the project, thus this background will help in its usage.

Optocoupler (2015): "*Optocouplers: When and How to Use Them*." Electus Distribution. 2 Sept. 2015
[Web] http://www1.electusdistribution.com.au/images_uploaded/optocoup.pdf
The data sheet describes optocouplers, gate drivers, which essentially are switching devices. It gives a brief background and how to use the device. Also, it provides diagrams that relate to the usage of an optocoupler. This specific gate driver will be used in the project to control 24V through 5V pulses.

Purdum, Jack (2012): "*Beginning C for Arduino*". New York: Technology in Action, 2012. Print.
This information gives basics for using Arduino and coding using C. As the computational part of the project will use Arduino, this information will help as a guideline for coding.

Rahimo, M.T., and N.Y.A. Shammas (2001): "*Freewheeling Diode Reverse Recovery Failure Modes in IGBT Applications*." IEEE Transactions on Industry Applications 37 (2001).
This article describes the use of the freewheeling, flyback, or suppressor diode. The use of which is required to restrict the sudden voltage spike across an inductive load when the supply voltage is suddenly removed or switched. Its use will be necessary in this project to prevent damage to the control circuit from voltage spikes.

Salazar, Fernando (1998). "Internal Combustion Engines": 9 Sept. 2015.
[Web] https://www3.nd.edu/~msen/Teaching/DirStudies/Engines.pdf
The research paper explains how Internal Combustion Engines (ICEs) work. Going over topics such as pistons, Engine Cycles, types of fuels and combustion, it details the specific parts of an ICE and their function. Specifically, detail on the Two Stroke Engine will help with designing the engine with the combination of an ICE and an electric motor drive.

TLP250 (2004): "TLP250 *Toshiba Photocoupler*". Toshiba, 25 June 2004.
[Web] http://web.itu.edu.tr/yildiri1/mylibrary/data/tlp250.pdf
The informative document on TLP250 (gate driver) gives the schematic, pin configurations and other data. Its use will be in the circuitry in the project. This information is essential as it helps obtain proper voltage flow that works toward the final project outcome.

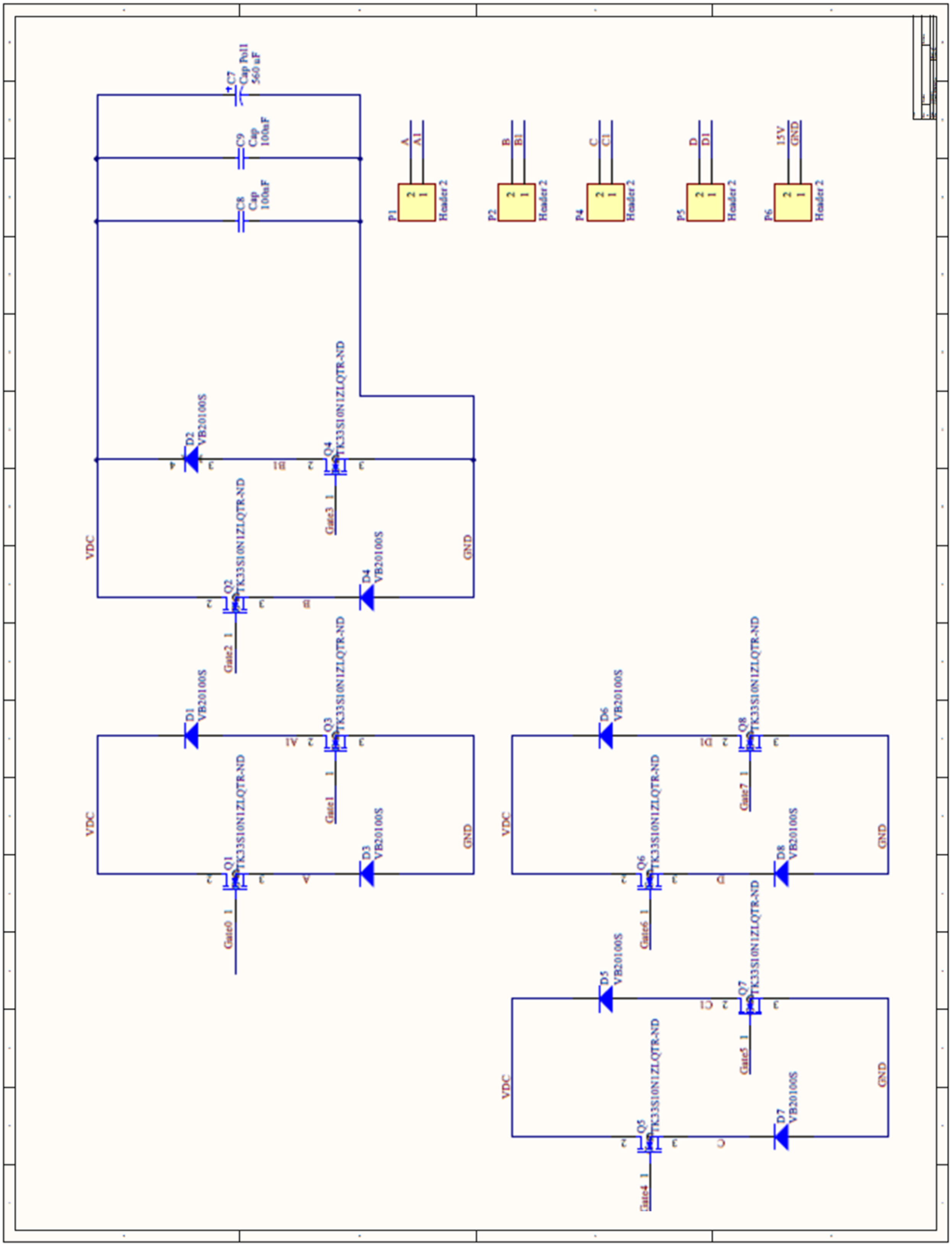
Timmis, H. (2011) *Practical Arduino Engineering.* Apress Publishing (www.apress.com), 2011.
This is a general technical reference which describes how to use of Arduino, its hardware and software environments, downloading and running a program, etc.

Union of Concerned Scientists (2015): "*How Hybrid Cars Work*." n.p. 21 Sept. 2015. [Web] http://www.ucsusa.org/clean-vehicles/electric-vehicles/how-do-hybrids-work#.VgOCjSBVhBd
This article talks about the current hybrid car, explaining the use of an Internal Combustion Engine simultaneously with the electric motor and battery. It explains some benefits of Hybrid Engines, which include fuel efficiency, regenerative-braking and power assist. Going further, it details the differences between a hybrid and an electric car engine. This information gives a general background on the current hybrid cars and their problems.

Universal Science Compendium (2015): "*Working Principles of the 2 Stroke and 4 Stroke Engines And Their Differences*." Automobile Compendium. 2 Sept. 2015 [Web] http://www.sciencecompendium.com/2014/03/working-principles-of-2-stroke-and-4.html
This article compares a two stroke engine against the functioning of a 4 stroke engine. Comparing the two working principles, it explains exhaust, piston pressure, and their differences and benefits. This helps in the design of the engine in the project.

VR 220 330 Service Operation Parts. Tulsa: Arrow Engine. 6, 8, 153, 155. Print.
This book references parts of an engine. Useful for specific parts such as: crankshaft, flywheel, pistons, and connection rod. It explains how to and what to troubleshoot in the mechanics of an engine. It gives proper logistics on these parts, which will be useful while designing the engine.

14. Appendix I – Schematic Diagrams for the Circuit Board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Cap Pol1
560 uF
C9
Cap
100nF
C8
Cap
100nF
P1
P2
P4
P5
P6
Header 2
A
A1
B
B1
C
C1
D
D1
15V
GND
VDC
GND
D1
D2
D3
D4
D5
D6
D7
D8
VB20100S
Q1
Q2
Q3
Q4
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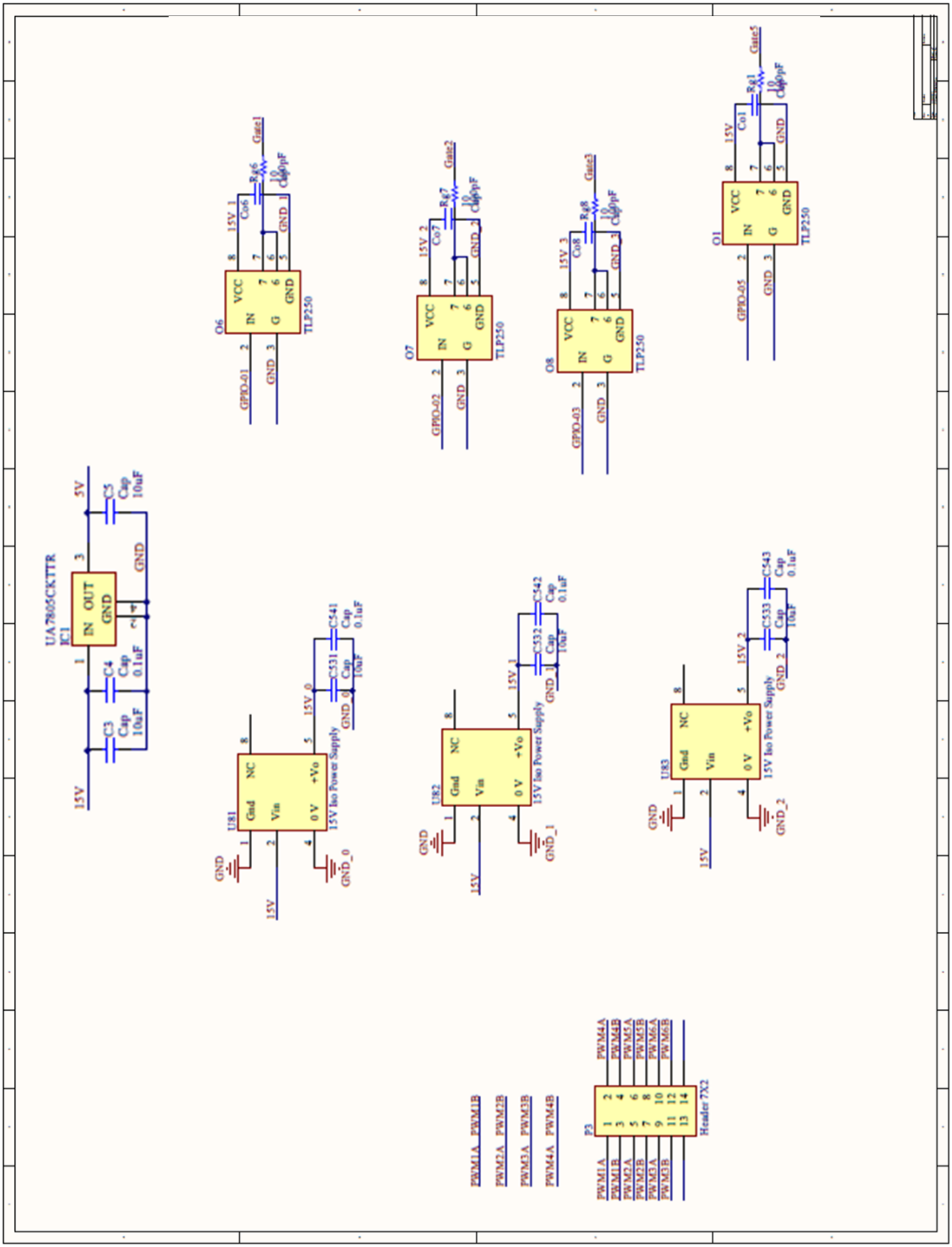
Gate6
Gate7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OUT
GND
15V
5V
GND
C3
Cap
10uF
C4
Cap
0.1uF
C5
Cap
10uF
Q6
VCC
IN
G
GND
TLP250
GPIO-01
GND_1
15V_1
Gate1
Co6
Rg6
Q7
TLP250
GPIO-02
GND_2
15V_2
Gate2
Co7
Rg7
Q8
TLP250
GPIO-03
GND_3
15V_3
Gate3
Co8
Rg8
Q1
TLP250
GPIO-05
15V
Gate5
Co1
Rg1
U81
U82
U83
Gnd
Vin
0 V
NC
+Vo
15V Iso Power Supply
15V_0
GND_0
C531
C541
C532
C542
C533
C543
GND_1
GND_2
P3
Header 7X2
PWM1A
PWM1B
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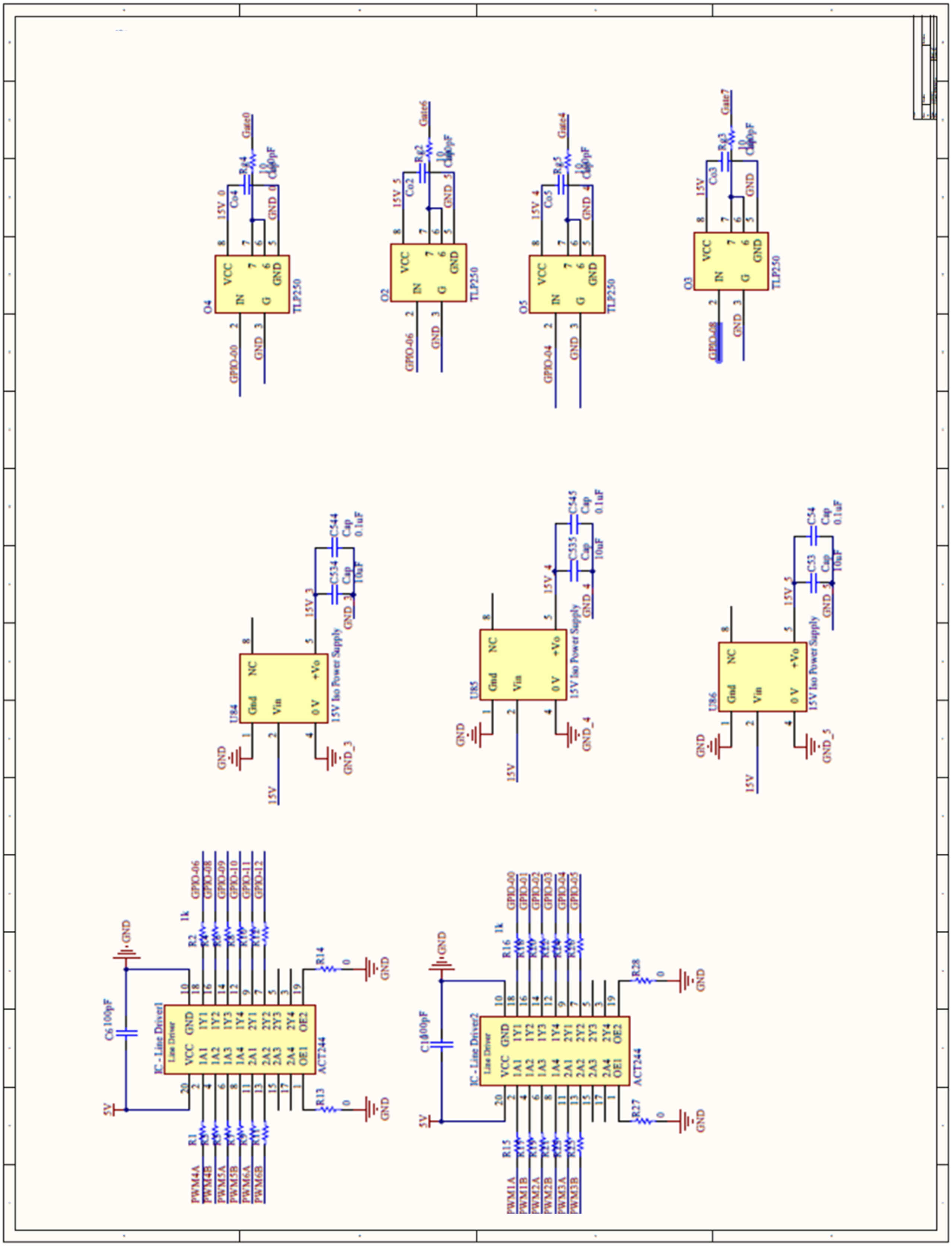
PWM6A
PWM6B



TLP250
15V Iso Power Supply
IC - Line Driver1
IC - Line Driver2
ACT244

15. Appendix II – Arduino UNO Microcontroller Code

15.1 2-Cylinder Oscillation Code

```
int outPIN1 = 13;
int outPIN2 = 12;d
int del = 300;

void setup() {
  // put your setup code here, to run once:
pinMode (outPIN1, OUTPUT);
pinMode (outPIN2, OUTPUT);
digitalWrite (outPIN1, LOW);
digitalWrite (outPIN2, HIGH);

}

void loop() {

        delay (del);

        digitalWrite (outPIN1, HIGH);
        digitalWrite (outPIN2, LOW);

        delay (del);

        digitalWrite (outPIN1, LOW);
        digitalWrite (outPIN2, HIGH);
}
```

15.2 4-Cylinder Engine Code (V4 and Boxer)

```
int outPIN1 = 10;
int outPIN2 = 13;
int outPIN3 = 11;
int outPIN4 = 12;
                          //Variables
float del = 3;            //Delay between on-off
int sdel = 50;            //Delay between fires

void setup() {
        pinMode (outPIN1, OUTPUT);
        pinMode (outPIN2, OUTPUT);
        pinMode (outPIN3, OUTPUT);
        pinMode (outPIN4, OUTPUT);
        digitalWrite (outPIN1, LOW);
        digitalWrite (outPIN2, LOW);
        digitalWrite (outPIN3, LOW);
        digitalWrite (outPIN4, LOW);
        Serial.begin (9600);
}
                          //Infinite Loop of PWM
void loop() {
        Serial.print(del);
        Serial.print("\n");
        digitalWrite (outPIN1, HIGH);
        delay (sdel);

        digitalWrite (outPIN1, LOW);
        delay (del);
        digitalWrite (outPIN4, HIGH);
        delay (sdel);

        digitalWrite (outPIN4, LOW);
        delay (del);
        digitalWrite (outPIN3, HIGH);
        delay (sdel);

        digitalWrite (outPIN3, LOW);
        delay (del);
        digitalWrite (outPIN2, HIGH);
        delay (sdel);

        digitalWrite (outPIN2, LOW);
        delay (del);
}
```

15.3 4-Cylinder Engine Code (Potentiometer)

```
int outPIN1 = 10;
int outPIN2 = 13;
int outPIN3 = 11;
int outPIN4 = 12;
int potPin = 1;

int del = 3;
int sdel = 0;
void setup() {
        pinMode (outPIN1, OUTPUT);
        pinMode (outPIN2, OUTPUT);
        pinMode (outPIN3, OUTPUT);
        pinMode (outPIN4, OUTPUT);
        digitalWrite (outPIN1, LOW);
        digitalWrite (outPIN2, LOW);
        digitalWrite (outPIN3, LOW);
        digitalWrite (outPIN4, LOW);
        Serial.begin (9600);
}

void loop() {
sdel = analogRead(potPin);

 if (sdel < 26)
         {
          sdel = 26;
         }
else {
        if(sdel > 500)
                {
                        sdel = 500;
                }
        else
                {
                         sdel = analogRead(potPin);
                 }
        }
```

```
Serial.print(sdel);
Serial.print("\n");

Serial.print(del);
Serial.print("\n");
                //Change following for specific engine and
firing order
digitalWrite (outPIN1, HIGH);
delay (sdel);

digitalWrite (outPIN1, LOW);
delay (del);
digitalWrite (outPIN4, HIGH);
delay (sdel);

digitalWrite (outPIN4, LOW);
delay (del);
digitalWrite (outPIN3, HIGH);
delay (sdel);

digitalWrite (outPIN3, LOW);
delay (del);
digitalWrite (outPIN2, HIGH);
delay (sdel);

digitalWrite (outPIN2, LOW);
delay (del);
}
```

15.4 HALL-EFFECT Sensor (Counter)

```
int HALL = 3;
int LED = 13;

int HALLin = 0;
int counter = 0;
int HALLstate = 0;
void setup (){
 pinMode (LED, OUTPUT);
 pinMode (HALL, INPUT);
 Serial.begin (230400);
}

void loop (){
 HALLin = analogRead (HALL);
  if (HALLin > 200)
  {
   HALLstate = 0;
  }
  else
  {
   if (HALLstate == 0)
   {
    counter++;
    Serial.print(counter);
    Serial.print("\n");
    HALLstate = 1;
   }

  }
}
```

15.5 HALL-EFFECT Sensor (RPM)

```
unsigned long time_since_last_reset = 0;
int interval_one = 10000;
int interval_two = 1;
int HALL = 3;
int LED = 13;

int HALLin = 0;
int counter = 0;
int HALLstate = 0;
int RPM = 0;

void setup(){
          pinMode (LED, OUTPUT);
           pinMode (HALL, INPUT);
           Serial.begin (230400);
}
void loop(){                                        //Main Loop (Set seconds,
count)
          time_since_last_reset = millis();
          while((millis() - time_since_last_reset) < interval_one)
                    {
                    HALLin = analogRead (HALL);
                    if (HALLin > 200)
                              {
                              HALLstate = 0;
                              }
                    else
                              {
                              if (HALLstate == 0)
                              {
                    counter++;
                    HALLstate = 1;
                    }
   }
}
  time_since_last_reset = millis();                 //Calculate RPM
           while((millis() - time_since_last_reset) < interval_two)
                    {
                    RPM = counter * 6;
                    Serial.print (RPM);
                     Serial.print ("\n");
                    counter = 0;
                    }
}
```

Science Fair 2016

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