2018 ASEE ANNUAL CONFERENCE & EXPOSITION
JUNE 24–27, 2018
SALT PALACE CONVENTION CENTER
SALT LAKE CITY, UT

Paper ID #21030

BYOE: The Fidget Car—An Apparatus for Small-group Learning in Systems and Controls

Prof. Laura E. Ray, Dartmouth College

Dr. Ray is a professor of engineering sciences at the Thayer School of Engineering, Dartmouth College. She received her B.E. and Ph.D. degrees from Princeton Univ. and her M.S. degree from Stanford University. She is a co-founder of two companies. Her research and teaching interests include control theory, mechatronics, and robotics.

Raina White, Dartmouth College

Raina White is an Engineering Lab Instructor at Dartmouth College. She earned a BS in Mechanical Engineering and a M.Eng in Systems engineering from Cornell University. She worked as a Systems Engineer at Hamilton Sundstrand, and then transitioned to teaching high school Physics. Currently Mrs. White works with students at Dartmouth College in systems, fluids, mechanical engineering, and automotive engineering courses and projects. She is very interested in improving student's ability to translate coursework into analysis applied to the design process.

Dr. David M. Feinauer P.E., Norwich University

Dr. Feinauer is an Assistant Professor of Electrical and Computer Engineering, and the Freshman Engineering Coordinator at Norwich University. His scholarly work spans a number of areas related to engineering education, including P-12 engineering outreach, the first-year engineering experience, and incorporating innovation and entrepreneurship practice in the engineering classroom. Additionally, he has research experience in the areas of automation and control theory, and system identification. His work has been published through the American Society for Engineering Education (ASEE) and the Institute for Electrical and Electronics Engineering (IEEE); he is an active member of both organizations. He serves as advisor to the student entrepreneurship club and as the State Partner for the FIRST LEGO League Program—a nationally recognized program that incorporates robotics with innovation and community engagement. He holds a PhD and BS in Electrical Engineering from the University of Kentucky.

Mr. David A. Hodgson, Union College
Dr. Eric B. Welch, Christian Brothers University
Dr. Yeu-Sheng P. Shiue, Christian Brothers University

Paul Shiue, Ph.D., is a Professor of Mechanical Engineering and Department Chair at Christian Brothers University in Memphis, TN. He earned his Ph.D. from the University of Memphis. Dr. Shiue spent five summers as a NASA/ASEE Summer Faculty Fellow at Marshall Space Flight Center. His interests include concurrent engineering, manufacturing, product realization processes, dynamics, vibrations, and material testing.

Dr. Carlos L. Luck, University of Southern Maine
Mr. Jonathan West, University of New Mexico
Dr. Blair T. Allison, Grove City College

Blair T. Allison is a Professor of Mechanical Engineering at Grove City College. He teaches courses in system dynamics, control systems, robotics, mechanics of materials, materials science, and finite element analysis. Areas of research interest include the modeling and control of metal forming processes, manufacturing automation and control systems. He received his Ph.D. and M.S. degrees in mechanical engineering from the Massachusetts Institute of Technology and his B.S.M.E. degree from Carnegie Mellon University. Address: 100 Campus Drive, Grove City, PA 16127; Email: btallison@gcc.edu.

Prof. Kevin Huang, Trinity College

Kevin Huang received the B.S. in Engineering and Mathematics from Trinity College, and the M.S. and Ph.D. in Electrical Engineering with concentration in Systems, Controls and Robotics at the University of Washington. His research focuses on evaluating haptic feedback, virtual fixtures and usability in telerobotic tasks, and exploring human factors in human robot interaction.

Dr. Nathan Amanquah, Ashesi University College

Nathan Amanquah is a Senior Lecturerin the Electrical Engineering Department of the Ashesi University College. He teachings a number of electrical engineering courses including Electronics, and Electrical Machines. He has previously taught Computer Networks, Mobile Web Programming and advanced programming classes for 13 years. He has previously worked as a systems administrator, a communications engineer and as an automation engineer. He has 20+ years of experience as a software developer and is a consultant on a wide range of mobile, information technology and telecommunications issues. He holds a BSc and a PhD in Electrical and Electronic Engineering from the (Kwame Nkrumah) University of Science and Technology, Ghana, and the University of Strathclyde, UK, respectively.His research includes 1)Wireless technologies and protocols for IoT and wireless sensor networks, 2) Mobile Apps for development: Improving outcomes in health, education and agriculture using mobile applications.

Mr. Daniel Logan Ray
Devin Tracey Montgomery, Dartmouth College

I am currently studying electrical engineering at Dartmouth College. During my first year, I was involved in a few extracurricular activities which included National Society for Black Engineers (NSBE), Afro-American-Society (AAm), and Club Basketball. As Programs Chair on NSBE I was responsible for networking with other chapters and determining new ways to involve our campus chapter with opportunities outside of Dartmouth. As Communications Chair on the AAm, I was responsible for interacting with several groups outside of the AAm community in order to encourage more external participation within the club. Many of my tasks included speaking with the African students on campus as well as some of the athletes. I planned and hosted an event with the black athletes on campus to discuss ways in how our two organizations were different and how we could assist each other. Also during my freshman year, I participated in First Year Research in Engineering (FYRE) which allowed me to work with Professor Laura Ray on ”Fidget Cars.” These cars were designed for a course at Dartmouth to help teach control theory, functions of controllers, as well as some other basic math and physics applications. The work done on this car ranged from working in the machine shop to build parts, testing motor characteristics, circuit design, and more. After participating in this project for most of the year, I plan to integrate computer science and mechanical engineering into my curriculum in aspiration of becoming a mechatronics engineer in the future.

Dr. Prudence Merton, Dartmouth College
Dr. Vanessa Svihla, University of New Mexico

Dr. Vanessa Svihla is a learning scientist and assistant professor at the University of New Mexico in the Organization, Information & Learning Sciences program, and in the Chemical & Biological Engineering Department. She served as Co-PI on an NSF RET Grant and a USDA NIFA grant, and is currently co-PI on three NSF-funded projects in engineering and computer science education, including a Revolutionizing Engineering Departments project. She was selected as a National Academy of Education / Spencer Postdoctoral Fellow. Dr. Svihla studies learning in authentic, real world conditions; this includes a two-strand research program focused on (1) authentic assessment, often aided by interactive technology, and (2) design learning, in which she studies engineers designing devices, scientists designing investigations, teachers designing learning experiences and students designing to learn.

BYOE: The Fidget Car – An Apparatus for Small Group Learning in Mathematics, Systems and Controls

Contact Information

Please contact Laura Ray, Thayer School of Engineering, Dartmouth College, lray@dartmouth.edu, for assistance with Fidget Cars.

Abstract

We present the *Fidget Car* – a one degree-of-freedom car driven by a DC motor – for use in small group laboratory exercises or classroom-based small group learning activities of 10-40 minutes in length. These activities can be directed towards a number of STEM courses, ranging from undergraduate mathematics or introductory engineering to systems and controls classes in electrical and mechanical engineering. The motivation for developing these activities is to enable students to develop intuition regarding core systems and controls concepts prior to or integrated with presentation of mathematical concepts and analysis techniques: the activities are designed to enable students to "visualize" the mathematics of systems. We provide an overview of the Fidget Car design, a materials list, example activities and use cases for the Fidget Car, and a pointer to a Google site archiving materials for reproducing and using the Fidget Car. We illustrate approaches for data acquisition and analysis that incorporate only a smartphone, a laptop, and open-source physics software, enabling activities to be conducted in a classroom setting.

Introduction

Systems and controls classes are often difficult for engineering undergraduates owing to mathematical rigor coupled with few opportunities to intuit system response characteristics. While many undergraduate systems and controls courses incorporate a course in differential equations as a prerequisite, often the math is integrated within the systems class, or, if a prerequisite math course exists, that course rarely includes elements that enable students to develop physical intuition regarding system response characteristics. The Fidget Car was developed to address the need for activities that enable students to develop insight regarding first- and second-order system response characteristics and effects of common nonlinearities, such as saturation, friction, and differentiable sensor nonlinearities. The cohort of authors worked together during a weeklong summer workshop to develop and refine learning activities to be used with the car. The activities build on each other, such that students must recall concepts from earlier activities as they perform later activities to aid learning. We see use cases for the Fidget Car ranging from first-year engineering mathematics to upper-level courses in control theory. In this paper, we cover the design and development of the Fidget Car and exemplar activities that can be targeted towards students at different stages within an undergraduate engineering program. A companion paper [1] details a sequence of activities specifically for systems and controls education.

Fidget Car Apparatus

The Fidget Car, shown in Fig. 1, is comprised of readily available components with the exception of a custom power amplifier and four simple machined parts, including an L-bracket chassis, a base plate, a sensor mount, and a mount for an optional tachogenerator. Figure 2 provides a schematic for the power amplifier, and Fig. 3 shows partial drawings for the four parts indicating material dimensions. The Fidget Car is designed around a common 12 V DC motor (7750 RPM no load speed) and a 60:14 timing belt drivetrain that drives a rigid axle. Axles are supported by miniature ball bearings mounted within bearing housings fastened to the chassis L-bracket with machine screws and are secured laterally using shaft collars. Wheels are mounted directly to hubs fastened to axles with setscrews and secured laterally using retaining rings. The toolset required to assemble the mechanical system includes allen wrenches, a small screwdriver, needlenose pliers, and retaining ring pliers.

The electrical system schematic is shown in Fig. 4. Two 12V NiMH batteries provide $\pm$12V and ground. The power bus is fabricated from a small piece of perfboard onto which an 18 position terminal block is soldered establishing connections for +12V, -12V ground, and the motor through switches. Both the power bus and switches are integrated within the sensor mount. A Sharp infrared sensor provides a voltage inversely proportional to distance from a target in front of the sensor. Figure 5 (from [2]) shows the voltage-distance relationship. The sensor is designed to be used in the nonlinear range of Fig. 5, and thus it is set back from the front of the car so that the linear region from 0 to ~5 cm is avoided. A 5V regulator integrated with the power bus provides sensor power and ground. The Fidget Car includes a summing junction housed in a “black box” and a prototyping board for implementing series compensators, although the summing junction can easily be implemented on the prototyping board at a cost savings of approximated $15 per car. A summing junction schematic with buffered inputs is shown in Fig. 6 and can be based on a general purpose operational amplifier, such as the LM741. The prototyping board mounted on top of the summing junction in Fig. 1 is fused so that the board, the power amplifier, and the summing junction circuits are protected from accidentally shorting a power or ground line. The two toggle switches enable control of power to the system and power to the motor separately, such that students can debug control circuits with the motor off. The linear power amplifier provides up to 3 A of current to the motor and accepts signal voltages of up to 12 V. The power amplifier gain is adjustable through a trim pot.

The Fidget Car is designed as an “all in one” apparatus with associated activities that can be integrated throughout a systems and control curriculum. A Google site [3] archives handouts and assessments developed for learning activities; a video showing assembly of the car; datasheets; materials list; and schematics for reproducing the car. 66 cars have been distributed to authors since July 2017, and an additional 20-25 cars are available for distribution to other faculty members interested in adopting the activities described herein. A materials list for the car is provided in Table A.2 and lists two sources for most parts. One source is for production in small quantities (~1-19 cars), and a second leverages quantity pricing for production in large quantities (20+ cars). A parts list for the power amplifier is provided in Table A.1. The approximate per-car cost is $350 in small quantities and $230 in large quantities. Learning activities for a control theory class require a kit of parts that includes a variety of resistor and capacitor values ranging from 1 kΩ to 3 MΩ and 0.01 μF to 10 μF; operational amplifiers; trim pots; solid wire of various colors; spare fuses; and a trim pot tool.

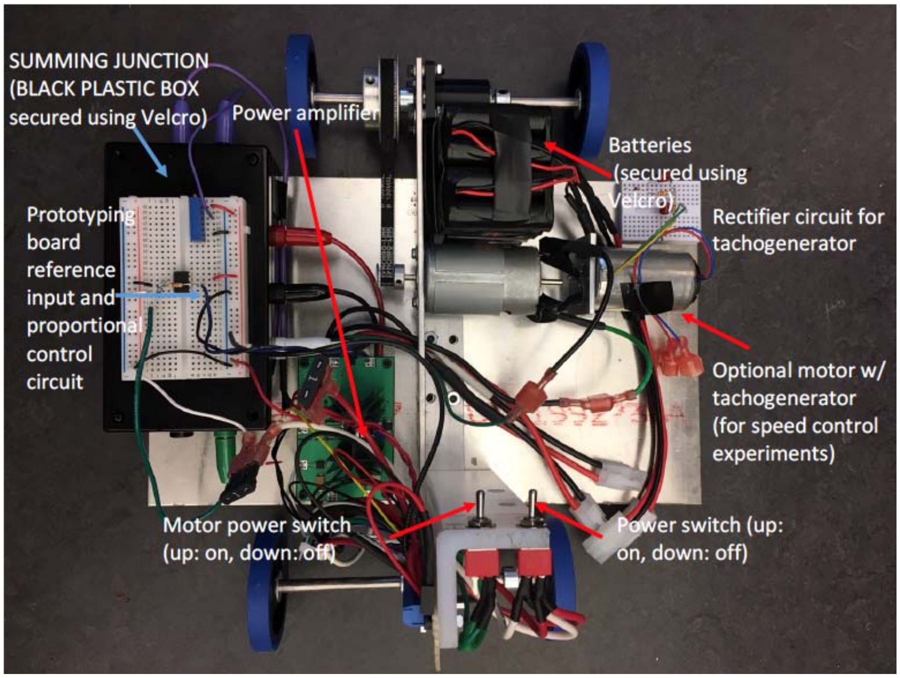


Figure 1 Fidget Car.

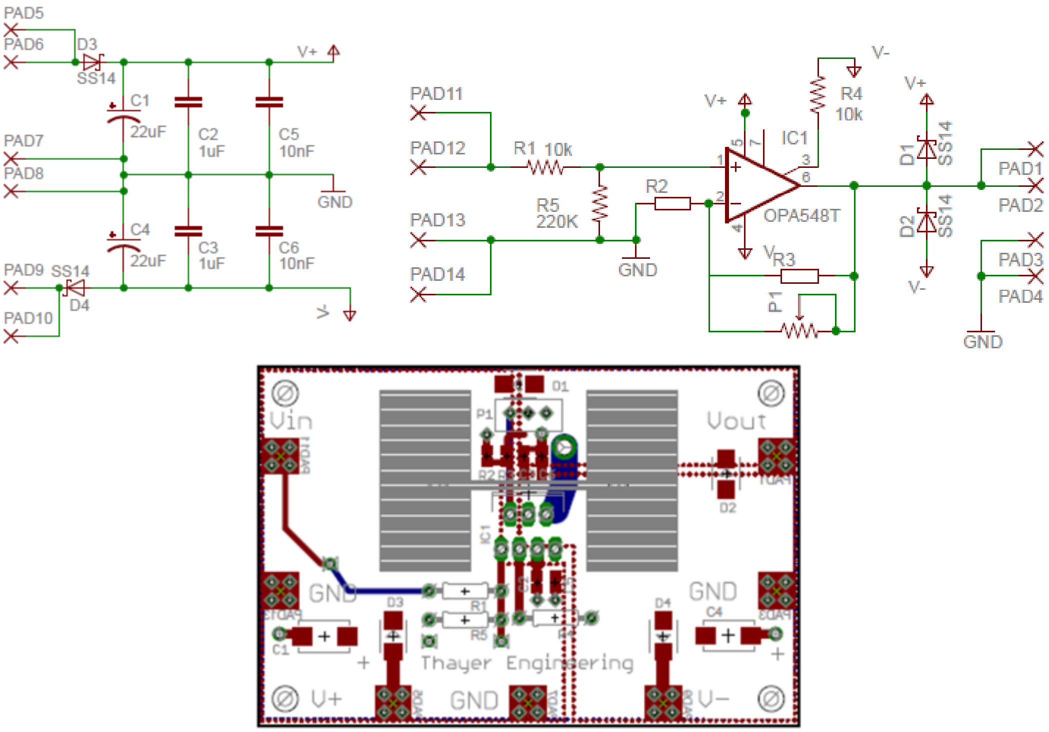


Figure 2 Power amplifier schematic and layout

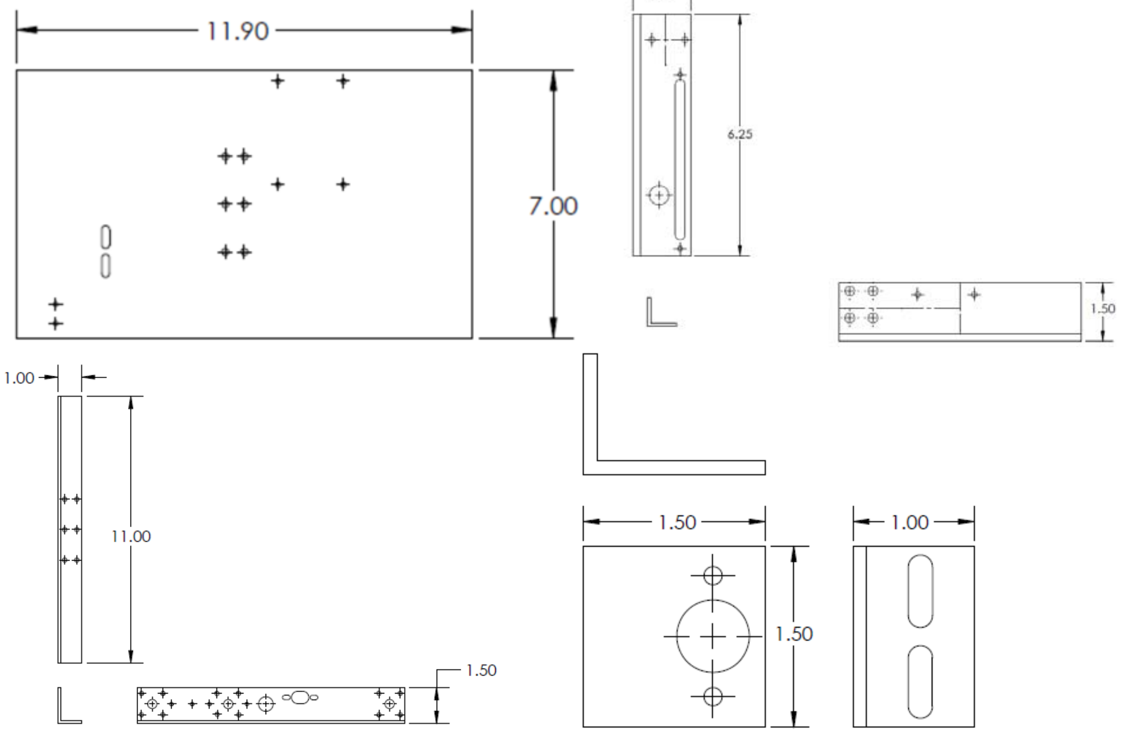


Figure 3 Partial drawings of the four machined parts. Top left: Aluminum base plate (1/16” thick), Bottom left: three views of aluminum L-bracket (1/8” thick); Top right: sensor mount (1/4” thick); Bottom right: optional tachogenerator mount. (1/8” thick). Dimensions in inches.

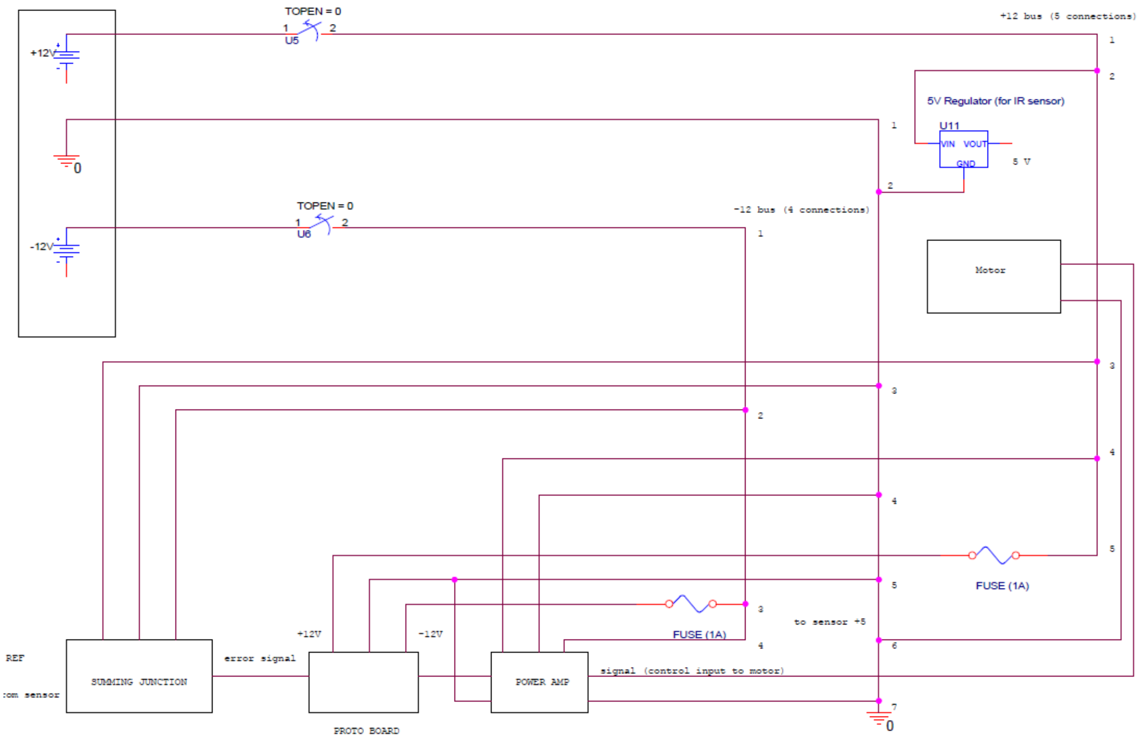


Figure 4 Electrical System Schematic.

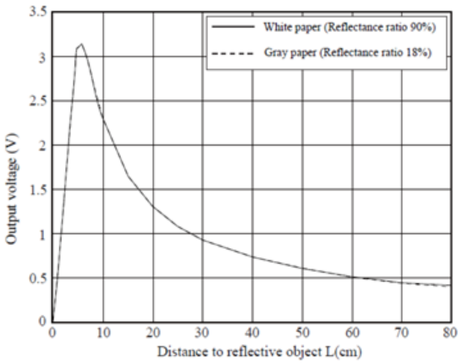


Figure 5 Sharp infrared sensor characteristics (from [2]).

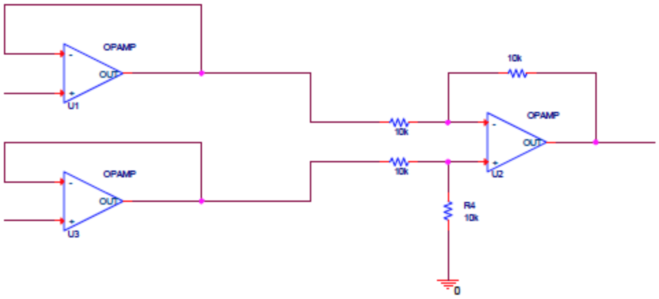


Figure 6 Summing junction with buffered inputs.

Fidget Car Dynamics and Example Learning Activities

The dynamics of the Fidget Car are governed by the DC motor driving a load (wheels on the ground) and are approximated by a first-order linear system describing the velocity $v(t)$ in response to a voltage input to the power amplifier V:

$$\tau\frac{dv}{dt} + v = KV \tag{1}$$

τ is the time constant (seconds) and K is the DC gain of the system, which includes the gain of the power amplifier. In addition, the dynamics include a number of common nonlinearities, including saturation (power amplifier and operational amplifiers), static and Coulomb friction between the wheels and the ground, and a differentiable sensor nonlinearity.

Measurement of the system parameters constitutes an introductory activity that can be used in courses ranging from a first course in engineering analysis to a junior or senior-level control theory course. In this activity, students apply open-loop step voltages of 2-6 V to the Fidget Car and acquire the open-loop response by using a stationary smartphone to video record the car's motion as it is released from rest. Students use free online tracker software [3] to extract position vs. time and velocity vs. time data from the video from which they can derive a time constant and DC gain, and compare the experimental response to the model response. Figure 7 shows a frame from a video of an overhead recording of the response along with example data. The tracker software automatically tracks a marker on the car (red tape in Figure 7) and uses a user-defined reference distance (tile length in Figure 7) to provide position vs. time and velocity vs. time in physical units. The process of taking a video, importing it into tracker, and extracting the data takes approximately 10 minutes once a student is familiar with the tracker software.

This activity can be conducted in a number of ways and can incorporate a number of learning objectives depending on class size, use of the activity in the classroom vs. as part of a laboratory, and instruction provided before, during, or after the exercise. Class size impacts the ability to perform the activity in the classroom, as the logistics of having a large number of Fidget Cars available may be impractical for lecture-based courses. However, even in a large class, a single Fidget Car can be used interactively, with student helpers, to obtain responses for two to three different voltages; the data can be immediately shared with the class for subsequent analysis in

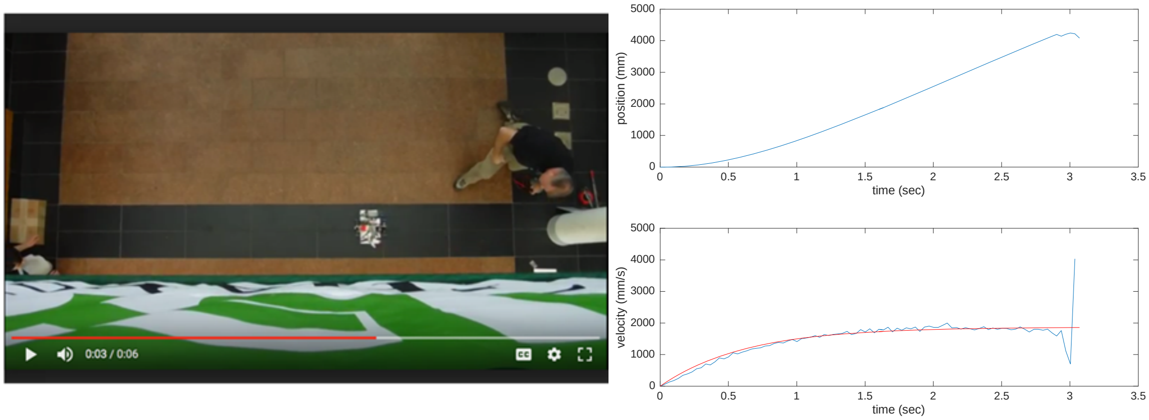


Figure 7 (a) Frame from a video of a system modeling exercise in progress, (b) Measured position and velocity data (blue) and first-order model response derived from the data (red).

small groups, and time constants and DC gains calculated by each group can be readily shared with the instructor for discussion and comparison among groups. An introductory engineering class whose learning objective for the activity is to learn to characterize first-order systems can begin the exercise with the solution to the differential eq. (1) rather than with the differential equation, since students have exposure to exponential functions in calculus. Students can then practice different methods to find the parameters of a solution of the form $v(t) = KV(1 - e^{t/\tau})$ given a constant voltage and known initial condition. Subsequent to the activity, the differential equation for the system may be introduced or derived from physical laws as a lead-in to the mathematics of first-order systems. In an upper-level course, groups may also evaluate linearity from a dataset comprising responses for several different voltages. We found that linearity holds well for voltages above ~3 V. Effects of static friction are illustrated by having students determine the minimum voltage at which the car moves.

While the velocity dynamics of the Fidget Car are first-order, position dynamics (as the integral of velocity) are second order. A second-order underdamped position response is readily portrayed by closed-loop feedback control of position with a proportional control gain of 4 to 8 V/V. The open-loop system transfer function between position and the input voltage to the power amplifier is

$$\frac{x(s)}{V(s)} = \frac{K}{s(\tau s+1)} \tag{2}$$

where $x(s)$ is the Laplace transform of position $x(t)$. The sensor provides a voltage inversely proportional to position, which, when linearized, provides a relationship between the linearized position and sensor voltage V_s:

$$V_s(t) = V_{s_o} + K_{sensor}(x(t) - x_o) \tag{3}$$

(x_o, V_{s_o}) is the operating point selected and K_{sensor} is the slope of Fig. 5 at the operating point. The sensor nonlinearity offers a learning opportunity related to linearization, which is commonly taught as a mathematical concept, i.e., use of the Taylor series, without understanding its implications within a system model. Here, students may use the sensor characteristics in Fig. 5 linearize the sensor model directly and determine its gain providing an alternate approach to understanding a first-order Taylor series approximation. In a separate exercise, students may also calibrate the sensor instead of using the curve given by the manufacturer. Note that K_{sensor} is negative for the infrared sensor leading to an additional learning opportunity – that of understanding the role of the negative sign in loop stability and how and where to change the sign if needed. In the Fidget Car, the sign of the feedback loop can be changed at the summing junction, by swapping the polarity of the motor, or placing an inverting, unity-gain op-amp in the loop.

With a proportional control gain K_p in the forward loop, the system open-loop transfer function is

$$\frac{x(s)}{V(s)} = \frac{K\, K_{sensor}\, K_p}{s(\tau s+1)} \tag{4}$$

where, *now* $x(s)$ represents the position *relative to* the operating point. The concept of a setpoint or operating point in control theory is an important, but often overlooked topic, and the Fidget Car provides a visual representation of the relationship between a reference input and the associated operating point. The closed-loop transfer function is

$$\frac{x(s)}{x_d(s)} = \frac{K\ K_p}{s(\tau s+1) + K\, K_{sensor}\, K_p} \tag{5}$$

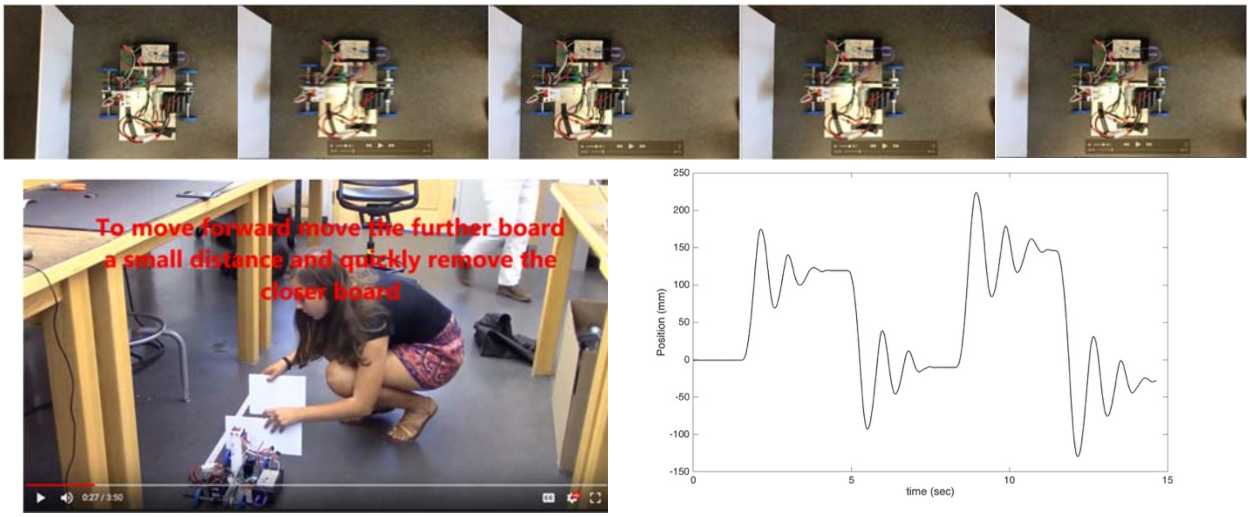
where $x_d(s)$ is the desired position. K_p is varied by replacing a single resistor. In an activity to characterize second-order response, students acquire closed-loop position vs. time data in response to a step input. The reference input to the summing junction is set using a trim pot, with voltage corresponding to the desired position of the car behind a physical target placed in front of the car, such as a foam core card. A close approximation to a step response incorporates two cards separated by known distance, e.g., 3-6 inches, with the car in its steady-state position behind a card. Sudden removal of the card closest to the car initiates a step response. The response of the car is captured by a stationary smartphone looking down on the car as it moves, and the tracker software is used to track a feature on the car providing position vs. time data. Figure 8 shows several frames of a step response video along with an example response and photograph of the experiment in progress.

Exercises with proportional control serve several purposes. First, they reiterate the concept of a closed-loop transfer function, and from this, they show that the characteristics of the response change by either changing the setpoint (setting K_{sensor}), or by changing the proportional control gain. Second, the experiment illustrates the response characteristics of a second-order system. Students can calculate second-order system transient response measures (peak overshoot, peak time, damping ratio, damped and undamped natural frequency, settling time) from the response and obtain a closed-loop transfer function and/or closed-loop roots as a function of gain. In an introductory systems class, the activity simply enables students to visualize second order response and to practice analyzing overdamped and underdamped systems using response measures. In a higher-level class, the activity can be extended to introduce root locus analysis by providing a series of responses that have a decreasing damping ratio as gain increases. These responses can be directly related to the closed-loop transfer function from which damping ratio, natural frequencies, and settling times can be predicted using measured DC gain K , the value of K_{sensor} given the setpoint, and the known proportional control gain K_p. Again, in a large class, the instructor can (using student assistants) acquire responses for a number of different control gains, distribute position vs. time data for a single gain to each group in the class for analysis, and plot points on the *s*-plane given damping ratio and natural frequency calculated by each group for each gain. The damping ratio and natural frequencies thus acquired trace out a root locus – illustrating the concept of a root locus before the concept is introduced mathematically, and reinforcing the root locus as a showing the locus of closed-loop roots as a system parameter varies.

Summary and Extensions

We have highlighted a few of the small group learning activities developed for the Fidget Car. Additional activities have been developed to provide a visual introduction to control theory; to motivate the need for system modeling; to introduce the concepts of steady-state error, sensitivity, system type, and disturbance rejection; and to develop series compensation using proportional integral, proportional derivative, PID, lead, and lead-lag compensators. These activities are described in detail in a companion paper [1].

An optional tachogenerator mounted axially with the drive motor in Fig. 1 provides for additional activities involving velocity control with a stationary system. The tachogenerator is comprised of an integrated DC motor and AC tachometer, which when rectified, provides a voltage proportional to speed. An optional inverted pendulum with a differential optical angle measurement circuit (not shown in Fig. 1) can be added to the Fidget Car for more advanced courses in control theory. The addition of these two elements provides an all-in-one apparatus for control of a first-order Type 0 system (velocity control of a DC motor), a second order Type 1 system (position control of the Fidget Car), and an unstable Type 0 system (Inverted pendulum).



To move forward move the further board a small distance and quickly remove the closer board

Figure 8 Top: Frames from the first half-cycle of oscillation in a video of the closed-loop step response for position control with a proportional controller, Bottom left: Screenshot of step response experiment n progress. Bottom right: Measured position response from the video for several consecutive step inputs (positive and negative commanded position values).

Acknowledgements

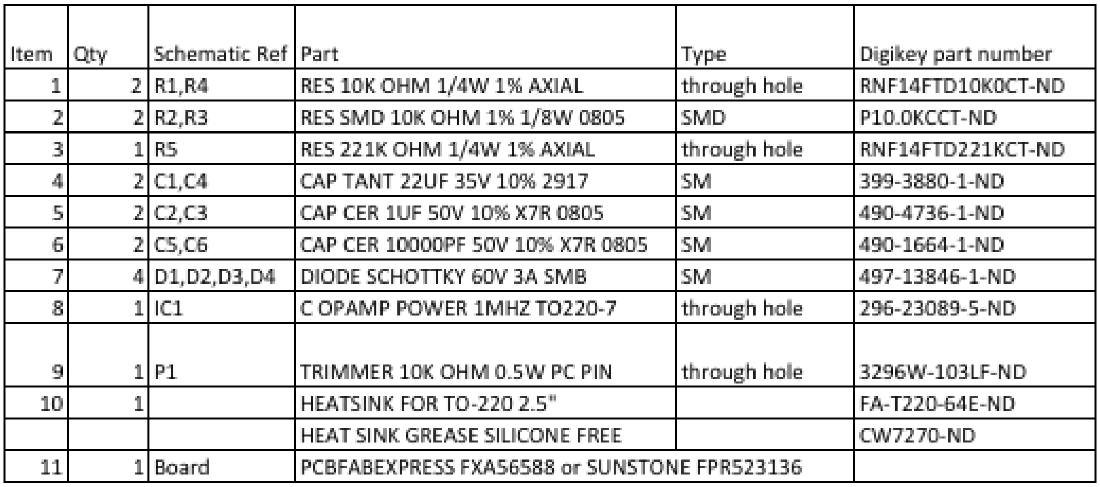
Funding for this project was provided by the National Science Foundation under Grant No. DUE-1611672 and the IEEE Control System Society Outreach Fund.

References

1. Laura Ray, David Hodgson, Raina White, Annett Gawerc, Prudence Merton, Devin Montgomery, Blair Allison, Nathan Amanquah, Charles Jackson, Fred McBagonluri, Paul Shiue, Eric Welch, David Feinauer, Kevin Huang, Carlos Luck, Jonathan West, Vanessa Svihla, Joshua Murphy, Daniel Ray, Small Group Learning Activities in Systems and Control Theory using Fidget Cars, American Control Conference, forthcoming, June 2018.
2. Sharp General Purpose Type Distance Measuring Sensors, GP2Y0A21YK0F, December 2006, datasheet E4-A00201EN.
3. Fidget Car Google Site. https://drive.google.com/drive/folders/1-EIhXfY8J2bLAuJHr90SYfBgbY7LaVAv?usp=sharing
4. D. Brown, Tracker Video Analysis and Monitoring Tool, https://physlets.org/tracker/, accessed December 11, 2017.

Appendix A. Materials List for Fidget Car

Table A.1 Power Amplifier Parts List

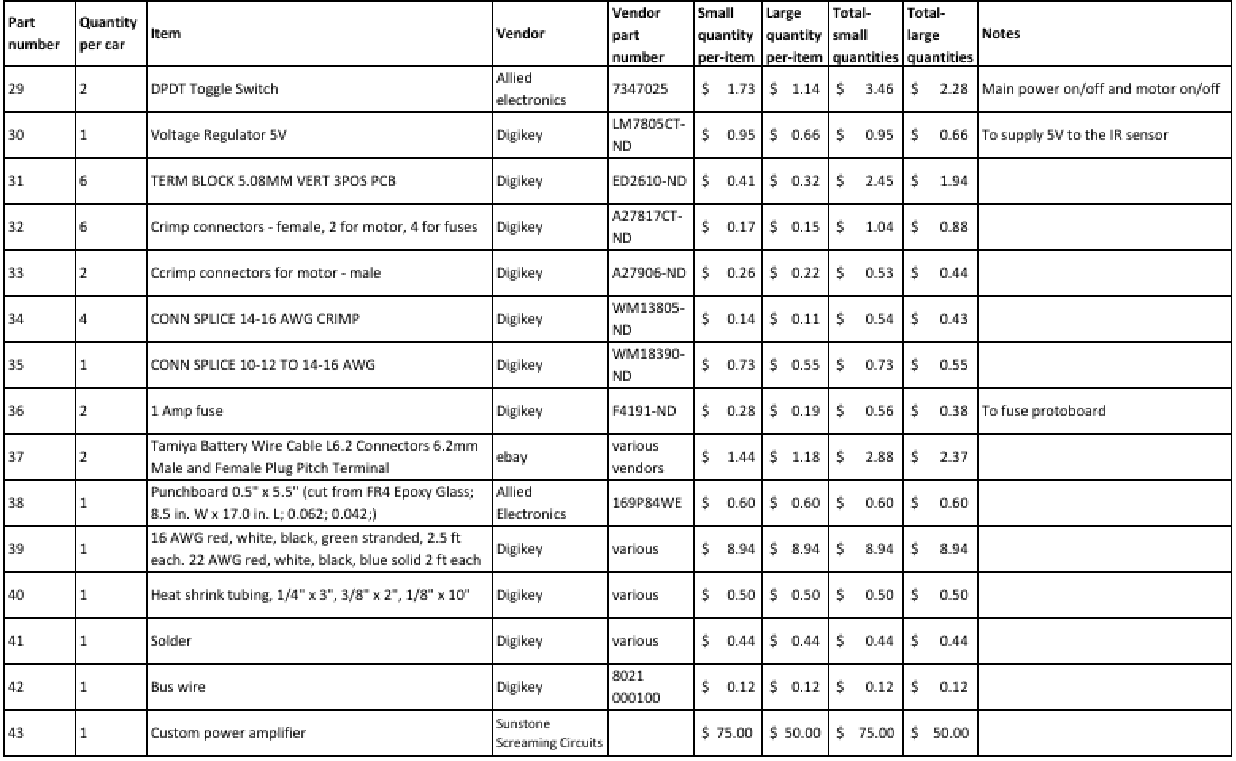


Item	Qty	Schematic Ref	Part	Type	Digikey part number
1	2	R1,R4	RES 10K OHM 1/4W 1% AXIAL	through hole	RNF14FTD10K0CT-ND
2	2	R2,R3	RES SMD 10K OHM 1% 1/8W 0805	SMD	P10.0KCCT-ND
3	1	R5	RES 221K OHM 1/4W 1% AXIAL	through hole	RNF14FTD221KCT-ND
4	2	C1,C4	CAP TANT 22UF 35V 10% 2917	SM	399-3880-1-ND
5	2	C2,C3	CAP CER 1UF 50V 10% X7R 0805	SM	490-4736-1-ND
6	2	C5,C6	CAP CER 10000PF 50V 10% X7R 0805	SM	490-1664-1-ND
7	4	D1,D2,D3,D4	DIODE SCHOTTKY 60V 3A SMB	SM	497-13846-1-ND
8	1	IC1	C OPAMP POWER 1MHZ TO220-7	through hole	296-23089-5-ND
9	1	P1	TRIMMER 10K OHM 0.5W PC PIN	through hole	3296W-103LF-ND
10	1		HEATSINK FOR TO-220 2.5"		FA-T220-64E-ND
			HEAT SINK GREASE SILICONE FREE		CW7270-ND
11	1	Board	PCBFABEXPRESS FXA56588 or SUNSTONE FPR523136		

Table A.2 Mechanical and Electrical Materials

Part number	Quantity per car	Item	Vendor	Vendor part number	Small quantity per-item	Large quantity per-item	Total-small quantities	Total-large quantities	Notes
1	1	RS-555 Motor 7750rpm 12V 29.16oz-in	Roboshop	RB-WTC-13	$ 6.71	$ 6.44	$ 6.71	$ 6.44	Rb-WTC-6 works too
2	1	Hardened Precision Steel Shaft, 1/4" Diameter, 20" Length	McMaster Carr	6061K417	$ 9.65		$ 9.65		Axles (cut to length) and optional pendulum mount
2	2	1/4 inch Dia. 304 Stainless Steel Round Bar 6"	Metals depot	R414		$ 0.53		$ 1.05	Axles (6 ft supplies 11-12 cars, cut to length) & optional pendulum mount
3	2	Aluminum Flange-Mount Housing for Linear Bearing, for 5/8" Bearing OD	McMaster Carr	9734K11	$ 22.56		$ 45.12		Bearing mounts & optional pendulum bearing mount
3	2	Aluminum Flange-Mount Housing for Linear Bearing, for 5/8" Bearing OD	Tarbell	phone order		$ 16.00		$ 32.00	Bearing mounts & optional pendulum bearing mount
4	1	Mxl Series Neoprene Timing Belt, .08" Pitch, 104 Trade Size, 10.4" Outer Circle, 1/4" W 104MXL025	B&B Manufacturing	130MXL025	$ 3.04	$ 1.59	$ 3.04	$ 1.59	Timing belt
5	1	Mxl and XL Series Timing-Belt Pulley, 1/4" Belt Width, 1.730 OD, 60 Teeth	B&B Manufacturing	60MP025-6FA3	$ 10.70	$ 5.89	$ 10.70	$ 5.89	bbman.com
6	1	Mxl and XL Series Timing-Belt Pulley, 1/4" Belt Width, .53" OD, 14 Teeth, 1/8" bore	B&B Manufacturing	15MP025-6CA2	$ 8.08	$ 4.30	$ 8.08	$ 4.30	Timing belt pulley
7	6	Mini High-Precision Stainless Steel Ball Bearing - ABEC-5, Flanged Open, 1/4" ID, 5/8" OD, .196" W	McMaster Carr	57155K305	$ 4.96		$ 29.76		Bearings for flange mounts
7	6	Mini High-Precision Stainless Steel Ball Bearing - ABEC-3, Flanged Open, 1/4" ID, 5/8" OD, .196" W	Alibaba	various vendors		$ 0.47		$ 2.81	Shanghai Promax Machinery Company Limited
8	1	Sharp 2Y0A21 Infrared distance sensor	Sparkfun	SEN-000242	$ 13.95		$ 13.95		10-80 cm range IR sensor
8	1	Sharp 2Y0A21 IR Package	ebay	various vendors		$ 3.75		$ 3.75	10-80 cm range IR sensor
9	4	Set Screw Shaft Collar, for 1/4" Diameter, Black-Oxide Steel	McMaster Carr	9414T6	$ 1.02		$ 4.08		
9	4	Set Screw Shaft Collar, for 1/4" Diameter, Black-Oxide Steel	Alibaba			$ 0.27		$ 1.09	Many vendors on Alibaba
10	4	BaneBots Wheel, 2-3/8" x 0.4", 1/2" Hex Mount, 50A, Black/Blue	Banebot	T40P-245BA-HS4	$ 2.75	$ 2.25	$ 11.00	$ 9.00	Banebot
11	4	Hub, Hex, Series 40, Set Screw,1/4" shaft, 1 Wide	Banebot	T40-SM61	$ 4.00	$ 3.28	$ 16.00	$ 13.12	Banebot
12	2	NiMH Battery Pack: 12V 2000 mAh	Tenergy.com	11606	$ 19.99	$ 15.50	$ 39.98	$ 31.00	Powers everything on car
13	2	Tenergy Smart Universal Charger for NiMH/NiCD Battery Packs 12V-24V (01027)	batteryjunction.com	01027-12-24V-CHG	$ 18.95	$ 17.45	$ 37.90	$ 34.90	Two chargers for two batteries
14	1	Architectural Aluminum (Alloy 6063), 90 Degree Angle, 3/16" Thickness, 1-1/2" X 1-1/2" Legs, 8'	McMaster Carr	88805K79	$ 2.91		$ 2.91		In 8' length @ 23.29 each
14	1	Architectural Aluminum (Alloy 6063), 90 Degree Angle, 1/8" Thickness, 1-1/2" X 1" Legs, 8'	Metals depot	A3112118-6063		$ 1.91		$ 1.91	In 16' lengths @ 30.62 each, cut to length
15	1	7" x 12" x 1/16" 6061 Aluminum plate - cut from 1/16" x 24" x 48" sheet	Online metals	1242	$ 3.05	$ 3.05	$ 3.05	$ 3.05	36.59 per sheet, cut to size
16	1	UHMW 90 Degree Angle 1-1/2" Outside Width, 1-1/2" Outside Height, 8 ft. Length	McMaster Carr		$ 1.32	$ 1.32	$ 1.32	$ 1.32	8 ft. length @ 23.84, cut to length
17	8	6-32 5/8" Socket cap screw, Black Oxide	McMaster Carr	91253A151	$ 0.08	$ 0.08	$ 0.68	$ 0.68	Couples bearing housing to L-bracket
18	4	4-40 1/2" socket head cap screw, black oxide	McMaster Carr	95868A311	$ 0.08	$ 0.08	$ 0.34	$ 0.34	To attach bus to sensor housing and sensor housing to car
19	3	6-32 3/8" Socket-head cap screw	McMaster Carr	91251A146	$ 0.08	$ 0.08	$ 0.25	$ 0.25	Plate to L bracket
20	8	4-40 Thread, 1/4" Length Black-Oxide Alloy Steel Socket Head Cap Screw	McMaster Carr	91251A106	$ 0.08	$ 0.08	$ 0.66	$ 0.66	Couples PCB to standoffs and standoffs to chassis plate
21	2	4-40 thread 1/2" length flat head screw black oxide	McMaster Carr	91253A110	$ 0.09	$ 0.09	$ 0.18	$ 0.18	
22	11	6-32 Hex Nut	McMaster Carr	90480A007	$ 0.01	$ 0.01	$ 0.14	$ 0.14	Between L-bracket and bearing housing
23	6	4-40 Hex nut	McMaster Carr	90480A009	$ 0.01	$ 0.01	$ 0.05	$ 0.05	Couples L-bracket to chassis plate
24	2	M03 x 0.5 mm thread 8 mm length slotted round head screws	McMaster Carr	90353A143	$ 0.03	$ 0.03	$ 0.06	$ 0.06	Motor to L bracket
25	4	Aluminum 4-40 standoffs	Digikey	36-2202-ND	$ 0.30	$ 0.20	$ 1.19	$ 0.82	Secure power amplifier to base plate
26	19	18-8 Stainless Steel Washer for Number 6 Screw Size	McMaster Carr	92141A008	$ 0.01	$ 0.01	$ 0.22	$ 0.22	
27	4	18-8 Stainless Steel Washer for Number 4 Screw Size	McMaster Carr	92141A005	$ 0.01	$ 0.01	$ 0.06	$ 0.06	
28	8	Zinc-Plated Steel Split Lock Washer for Number 6 Screw Size, 0.148" ID, 0.25" OD	McMaster Carr	91102A007	$ 0.00	$ 0.00	$ 0.04	$ 0.04	Bearing housing to L-bracket

Table A.2 (continued) Mechanical and Electrical Materials



Part number	Quantity per car	Item	Vendor	Vendor part number	Small quantity per-item	Large quantity per-item	Total-small quantities	Total-large quantities	Notes
29	2	DPDT Toggle Switch	Allied electronics	7347025	$ 1.73	$ 1.14	$ 3.46	$ 2.28	Main power on/off and motor on/off
30	1	Voltage Regulator 5V	Digikey	LM7805CT-ND	$ 0.95	$ 0.66	$ 0.95	$ 0.66	To supply 5V to the IR sensor
31	6	TERM BLOCK 5.08MM VERT 3POS PCB	Digikey	ED2610-ND	$ 0.41	$ 0.32	$ 2.45	$ 1.94	
32	6	Crimp connectors - female, 2 for motor, 4 for fuses	Digikey	A27817CT-ND	$ 0.17	$ 0.15	$ 1.04	$ 0.88	
33	2	Ccrimp connectors for motor - male	Digikey	A27906-ND	$ 0.26	$ 0.22	$ 0.53	$ 0.44	
34	4	CONN SPLICE 14-16 AWG CRIMP	Digikey	WM13805-ND	$ 0.14	$ 0.11	$ 0.54	$ 0.43	
35	1	CONN SPLICE 10-12 TO 14-16 AWG	Digikey	WM18390-ND	$ 0.73	$ 0.55	$ 0.73	$ 0.55	
36	2	1 Amp fuse	Digikey	F4191-ND	$ 0.28	$ 0.19	$ 0.56	$ 0.38	To fuse protoboard
37	2	Tamiya Battery Wire Cable L6.2 Connectors 6.2mm Male and Female Plug Pitch Terminal	ebay	various vendors	$ 1.44	$ 1.18	$ 2.88	$ 2.37	
38	1	Punchboard 0.5" x 5.5" (cut from FR4 Epoxy Glass; 8.5 in. W x 17.0 in. L; 0.062; 0.042;)	Allied Electronics	169P84WE	$ 0.60	$ 0.60	$ 0.60	$ 0.60	
39	1	16 AWG red, white, black, green stranded, 2.5 ft each. 22 AWG red, white, black, blue solid 2 ft each	Digikey	various	$ 8.94	$ 8.94	$ 8.94	$ 8.94	
40	1	Heat shrink tubing, 1/4" x 3", 3/8" x 2", 1/8" x 10"	Digikey	various	$ 0.50	$ 0.50	$ 0.50	$ 0.50	
41	1	Solder	Digikey	various	$ 0.44	$ 0.44	$ 0.44	$ 0.44	
42	1	Bus wire	Digikey	8021 000100	$ 0.12	$ 0.12	$ 0.12	$ 0.12	
43	1	Custom power amplifier	Sunstone Screaming Circuits		$ 75.00	$ 50.00	$ 75.00	$ 50.00	