AC 2009-89: ENGINEERING DESIGN: THE MECHATRONICS APPROACH AND COGNITIVE EXPERIENCE

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Engineering Design: The Mechatronics Approach and Cognitive Experience

Abstract

Mechatronics is a rapidly developing, interdisciplinary field of engineering dealing with design of products whose function relies on the integration of mechanical and electronic components coordinated by a control architecture. A mechatronics platform has strength through its ability to offer dynamic and flexible solutions. Engineers and educators are devising methods and means to capture and maintain student interests while providing them with a meaningful experiential learning. This article presents a mechatronics learning experience using everyday toy-like products such as Legos and wood yet delivering a lasting impact. This learning experience is based on mechanics and motor selection.

The fundamentals of engineering design such as statics and dynamics are presented. Further, design needs in electrical, and teamwork issues are addressed. The strength of the study is seen through a challenge presented that requires student innovation towards solving such problems. Students are provided opportunity for growth through thought and utilization of their knowledge to provide solutions to given problems. The activity brings relevance to Science, Technology, Engineering, and Math by showing its application to ordinary and complex solutions. This approach is not only fun to the students but is can be easily adapted to any STEM discipline in different educational levels. The learning experience could be the first in a series of learning mechatronics, which could be followed by introducing electronics, and programming, respectively. This paper is aimed for undergraduate level.

Introduction

Aliciatore and Histand defined mechatronics as an "interdisciplinary field of engineering dealing with the design of products whose functions rely on the integration of mechanical and electronic components coordinated by control architecture[1]. Mechatronics is rich in content, deep in specialty, and diverse that can be customized for varying learning levels, styles, and needs. Therefore, if you have ever wanted to easily integrate mechanical, electrical, programming, and controls to develop a dynamic toy or robot, then this article will provide you with basic direction towards developing learning experience for your students.

The objectives of the paper are to introduce mechatronics field in a way students can comprehend it in non threatening atmosphere; show value of the mechatronics field; indicate how STEM can benefit from mechatronics by adopting it as a synthesis learning area, such as capstone requirement; and assess student views on the subject matter. To provide this experience, the author presents a sample mechatronics challenge.

The Challenge

Design and build a motorized cart capable of pulling a load of 50 hex nuts up a 15^0 inclined after the load survives an impact at the bottom of the downhill section. Design for best performance.

Details: The course consists of an 11foot board inclined approximately 15^0. Construct a "tow-car" driven by a Lego motor and powered by a 9-volt battery, and a "trailer" capable of carrying 50 hex nuts. For downhill phase, the trailer will start behind the 1' marker at the top of the incline facing downhill loaded with 50 hex nuts and disconnected from the tow car. The trailer is released and rolls down the incline. At the bottom of the hill, it will impact a wall. If any parts of the car are dislodged the run is considered a failed attempt.

For the uphill phase, the tow car is connected to the trailer with a string. The trailer starts with its back end touching the wall at the bottom of the hill. The clock starts when the car begins to pull the trailer up the hill. The clock will stop when the trailer completely crosses the 1' line.

All 50 hex nuts must be carried on the trailer. The hex nuts cannot be constrained by running axle pieces through the holes. Either or both the car and the trailer may be two wheeled or four wheeled vehicles. The car can be either front wheel drive or rear wheel drive and sample is shown in figure 1.

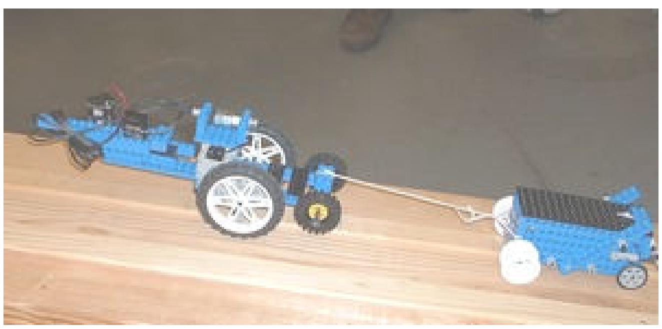


Figure 1: Motorized Cart Pulling Load up Incline

There are raised ridges on the board to help steering. One ridge is ¼" high, the other is ½" high. You decide whether your cart straddles one or both ridges, or rides between them. If the car jumps off the guiding ridge, it is considered a failed attempt.

All materials used must be carried by the cart, including the battery and wires. The hex nuts must be secured only with Legos. They cannot be carried in other bags or containers.

Materials

Materials include, One Lego motor as the sole means of propulsion; One 9-volt battery to power the motor; One pair of big, thin Lego wheels; and other Lego building supplies.

Approach and Design Process

Reviewing trigonometry and basic physics concepts about forces will prepare students to determine significant issues of the challenge, such as, "Stall Torque" and "No-load speed"; and estimated maximum power of the motor. For engineering students, review of statics and dynamics is very helpful for predictive analysis of the system.

Mechanics and motor selection are two basic engineering concepts being present. The design process requires iterations in each step for optimization. The first step was to design and build a trailer capable of securely hauling 50 hex nuts that survive the impact. Two key characteristics of the trailer design were the ability to haul the load, and to absorb the shock during impact while maintaining structural integrity. A basic four wheel trailer in the shape of a hollow box with a lid was built to house the hex nuts. To absorb energy upon impact, two spring-loaded Lego shock-absorbers were built into the rear section of the trailer as depicted in figure 2.

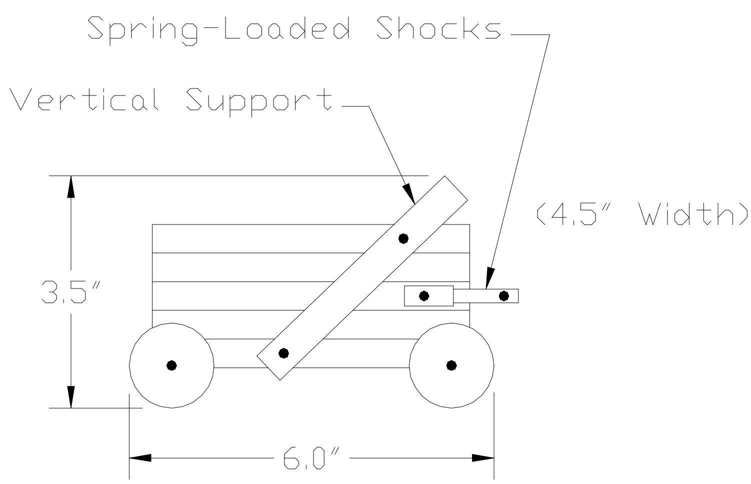


Figure 2: Side View of Trailer

In designing the motorized car, the first step was to calculate the ideal gear ratio to maximize power from the electric motor. Using information from http://www.philohome.com/motors/motorcomp.htm the peak power of the 43362 motor was determined to be approximately 0.6 W at 165 RPM. The motor torque at this speed is 0.0344 N.m. Expressed in radians per second, the ideal motor speed is

$$\omega_{motor} = (165\ rev/\min)\left(\frac{2\pi\ rad/\sec}{60\ rev/\min}\right) = 17.3\ rad/\sec$$

Calculation of the amount of work done to move the car and trailer up ten feet on a 15^0 incline as shown in figure 3 was necessary to determine the theoretical top speed of the car.

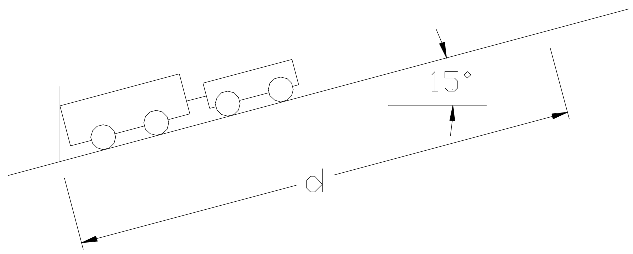


Figure 3: Schematic of Challenge

Neglecting friction, the ideal amount of work can be expressed as

$$W = F\ d_{effective} = m_{total}\ a\ d\ \sin(15°) \qquad (1)$$

Where m_{total} is the combined weight of the car, trailer and load, and d is equal to 10 feet or 3.05 meters. The ideal time, t, required to lift the combined mass, and the ideal speed of the car, v, are expressed, respectively, as

$$t = W / P_{motor} \qquad (2)$$

$$v = d\ /\ t = \omega_{drive\ wheel}\ r_{drive\ wheel} \qquad (3)$$

The gear ratio is defined as

$$\frac{N_{drive\ wheel}}{N_{motor}} = \frac{\omega_{motor}}{\omega_{drive\ wheel}} \qquad (4)$$

Combining equations (1), (2), (3) and (4), the theoretical gear ratio can be expressed as

$$\frac{N_{drive\ wheel}}{N_{motor}} = \frac{\omega_{motor}\ W\ r_{drive\ wheel}}{P_{motor}\ d} \qquad (5)$$

The total mass was estimated to be the sum of the masses of known components (motor, battery, and hex nuts) multiplied by a factor of 1.33 to account for the Lego's mass. This estimate was found to be around 550 grams. The radius of the drive wheel measured at 0.043 m.

Entering known values and mass into equations (5) and (2), the ideal gear ratio was found to be 1.72 and the ideal time to traverse the incline came to 7 seconds. A gear ratio of 5:1 was selected for initial trials factoring in friction.

In order to maximize the speed of the cart, the amount of work required to move the car, trailer and load up the incline should be minimized, while the utilization of motor power should be maximized. The selected gear ratio would efficiently transfer power from the motor to the drive wheels. However, in order to maximize the use of this power, a relatively high normal force is required at the drive wheels to prevent slippage.

An analysis of the car's free body diagram, shown in Figure 4, can provide answers on how to minimize the work required and maximize the normal forces on the drive tires.

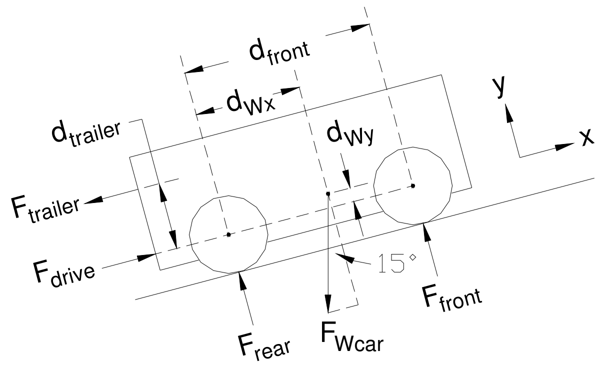


Figure 4: Free Body Diagram of Motorized Car

A sum of the forces in the x and y directions yields

$$\sum F_x = F_{drive} - F_{trailer} - F_{W\,car} \sin(15°) = 0 \qquad (6)$$

$$\sum F_y = F_{front} + F_{rear} - F_{W\,car} \cos(15°) = 0 \qquad (7)$$

Summing the moments about the rear axle yields

$$F_{front} = \frac{F_{W\,car}\ \cos(15°)\ d_{W\,x} - F_{W\,car}\ \sin(15°)\ d_{W\,y} - F_{trailer} d_{trailer}}{d_{front}} \qquad (8)$$

In order to minimize the work required, the force required to drive the cart up the incline, F_{drive}, should be minimized. Equation (6) shows that both minimizing the weight of the car and minimizing the drag force of the trailer, $F_{trailer}$, will help to achieve this aim.

Equation (7) shows that the total normal forces are directly proportional to the weight of the car. Increasing the weight of the car will increase the total normal forces, but unfortunately increases the force required to drive the car. Thus, a happy medium should be determined.

Additionally, equation (7) shows that the normal forces are distributed between the front and rear wheels. A front wheel drive car was chosen since basic calculations showed it to be favorable than rear wheel drive. Since the front set of wheels is used to drive the vehicle, it becomes favorable to support as much of the weight on these two wheels and minimize the normal forces on the rear tires in order to maximize efficiency.

Evaluation of equation (8) sheds light on additional ways to maximize the normal forces on the drive wheels without increasing the overall weight of the car. Analysis shows that this can be done by maximizing d_{Wx} and by minimizing d_{Wy} and $d_{trailer}$. (Refer to Figure 3.). An in-line gear train provided good performance.

Tire slippage was eliminated by using leverage to increase the normal force by further increasing d_{Wx}. The frame was redesigned to support a long beam resulting to minimzed d_{Wy} forces, and positioned the center of gravity infront of drive wheels as shown in figures 5 through 7. By connecting the trailer string at a low point on the back $d_{trailer}$ was reduced.

Rolling resistance was minimized by using cross members on top of and below the main support beams of the frame as shown in Figure 5. This provides alignment and rigidity, reducing friction on the vehicle axles. Steering is primarily done through the use small wheel hubs as a guide mechanism. These hubs are affixed to L-shaped bushings that mount to a fixed shaft as shown in figure 6. A counterweight built from a shaft and spare hex nuts also aids in steering as it balances the weight of the motor that is located on the left side of the vehicle.

The final combined weight of the car, trailer and load of hex nuts is 791 grams. This is significantly higher than the estimated weight used in the preliminary calculations. Recalculating with the new mass yields an ideal gear ratio of 2.5 and an ideal time to traverse the incline of 10.2 seconds.

Table 1 shows the vehicle velocity and motor velocity for all trials including and three competition runs (R1-R3). Calculations are derived from equation (3) and (4).

Table 1: Velocities for several Trial Runs

Trial	Time to climb 3 meters (sec.)	Vehicle Velocity (m/s)	Motor Velocity (rad/s)
1	32	0.09	10.9
2	30	0.10	11.6
3	24	0.13	14.5
4	26	0.12	13.4
5	22	0.14	15.9
6	20	0.15	17.4
R1	18.7	0.16	18.7
R2	18.3	0.16	19.1
R3	16.4	0.18	21.3

Friction reduction and improving steering and alignment resulted in faster runs (trials 3-6).

Discussion

If the challenge described above is viewed as an ordinary exercise, then it loses its objective. The exercise is intended to provide an environment to use several engineering concepts to develop a mechatronic product. Through developing a free body diagram of motorized car, as shown in figure 4, and making an analysis of the forces and summing up its moments, students were able to apply statics concepts into real life problem analysis. They used the results to determine and predict the speed of the vehicle. Further, they used motor data sheets to calculate and determine motor performance is an aspect of electrical and power needs. Through the testing of the vehicle robustness, students were able to develop a mechanical body, made of Legos, that had strength to withstand impact on downward impact test.

In the final analysis, students were able to appreciate the use of engineering concepts and translate them into real life problem solving experiences and applications. They were able to make an initial prediction of what it would take to carry the load on the incline plane and used results to further improve performance of the vehicle. The author was satisfied with the pedagogical approach as guided by Social Learning Theory (SLT).

Social learning theory states that learning can be attained through observation, imitation, and cognitive processes[2]. For the observation component, the author worked examples on the board to review statics and dynamics problems. Students were assigned homework problems related to statics and dynamics after observing the examples done by the author. The author reviewed about torque and speed needs in transportation. The author compared a semi truck with the task at hand to haul a load uphill. The truck they were to imitate would provide a platform to consider all the drive needs to accomplish the mechatronics challenge learning exercise successfully and effectively. The cognitive component in SLT plays a role in learning by shaping the state of reason or state of mind. Awareness and expectation of future reinforcements or punishments can have major effect on the behaviors that people exhibit. For example, reasons for successful completion of this learning exercise could have had variables such as winning the contest, getting a good grade, tying engineering concepts to real life problem solving, or simply satisfaction and confidence in mechatronics. Overall the motivation to conquer the challenge was paramount.

What mechatronics offer:

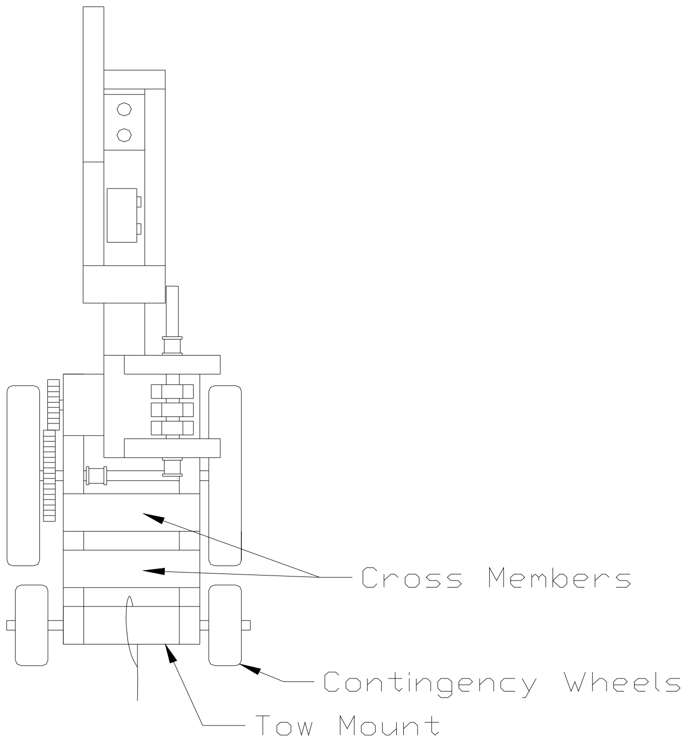
- Fun in the classroom –valued added to learning and fun through teamwork activities in Mechatronics and Animatronics respectively[3,4].
- Relevance and application to daily living – our life today cannot be delinked from technology advancements. Automatic door openers; photocopy machines; robots; escalators; automobiles; and more are mechatronically designed.
- Relevance to course connectivity - Mechatronics offers the seamless connectivity of Science, Technology, Engineering, and Math (STEM)[5, 6].
- Opportunity for growth for deeper design challenges through analytical prediction, simulation, and testing before actual construction of an artifact. Depending on the learning level, students can be challenged to investigate further in their learning experiences.

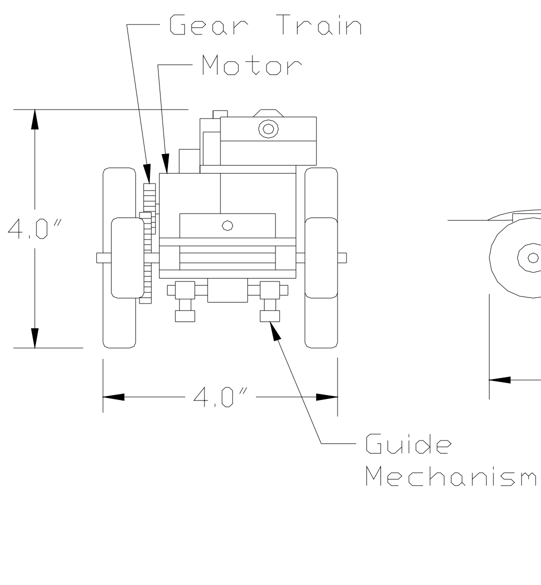
- Adaptation to various disciplines – Mechatronics lends itself to virtually any field, any product, and any process. Can be utilized in medical, entertainment, exploration, or product development.

Performance and Conclusions

The objectives were met in many ways, for example, students had fun in their work, as exemplified by spending time after class to work on their project without instructor push. They used their analytical skills to analyze their for example, they revised their statics and dynamics to make predictions of the project needs and performance before designing, constructing, and testing. They engaged in developing alternative designs of the motorized car and the truck as they analyzed and then settled to the one they found to be analytically sound. They saw the value in mechatronics as they discussed its application to daily life products and found numerous instances. The students' accomplishments in designing, construction, and testing their product successfully are an assessment in itself for a learning experience well done. This is an experience that you can engage your students with resulting to rewarding learning experiences. Learning the keeps the interest is a testament to a cognitive way of acceptance and understanding through observation, imitation, and development as advocated by the social learning theory. The author believes that learning takes place using mechatronics learning experiences, especially those that provide to the student an attitude of inquisitiveness, eagerness, and desire to understand how things get designed and work.

Figure 5: Top View of Motorized Tow-Car





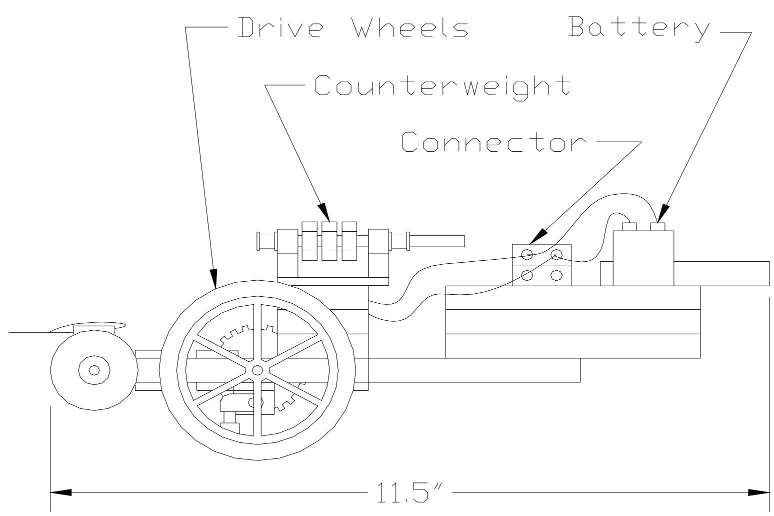


Figure 6: Rear View of Motorized Tow-Car

Figure 7: Side View of Motorized Car

Bibliography

1. Alciatore, D. G., & Histand, M.B. (2003). *Introduction to Mechatronics and Measurement Systems 2nd Edition*. McGraw-Hill Publsiher.

2. Bandura, A. (1977). Social Learning Theory. New York: General Learning Press.

3. Mativo, J. M. & Stienecker, A. (2007). Proceedings of the 2007 American Society for Engineering Education Annual Conference & Exposition. AC 2007-730: *Innovative Exposure to Engineering Basics through Mechatronics Summer Honors Program for High School Students*. Honolulu, HI. June 24 - 27, 2007.

4. Sirinterlikci, A & Mativo, J. M. (2006). Proceedings of the 2006 American Society for Engineering Education Annual Conference & Exposition. *Summer Honors Institute for the Gifted.* Chicago, IL. June 18 – 20, 2006.

5. Fontenot, A. D. & Chandler, J. (2005). *Partnering with K-12 Institutions to prepare School Teachers for Engineering Education*. ASEE/IEEE Frontiers in Education Conference. Indianapolis, IN.

6. Salinger, G. (2003). Engineering in K-12 curriculum. Paper presented at the American-Australian Technology Education Forum, Gold Coast, Australia. In Martin, G. & Middleton, H. (Eds.) (2003). Initiatives in Technology Education: Comparative Perspectives, pp. 88-96. Nathan, Queensland: Technical Foundation of America and the Center for Technology Education Research, Griffith University.