# 2020 DOE Hydrogen and Fuel Cells Program Review

# Autonomous Hydrogen Fueling Station

Project ID TA029

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Plug Power Inc.
June 12, 2020

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# Overview

## Timeline

Project Start Date: Oct 2018

Award Received: Mar 2019 (work started at this time)

Project End Date: Apr 2022*

*Project continuation and end date determined annually by DOE

## Budget

| | |
|---|---|
| Total Federal Share: | $1,797,216 |
| Total Recipient Share: | $549,547 |
| Total Project Budget: | $2,346,763 |
| Total DOE Funds Spent: | $226,378* |

*as of 3/31/2020

## Barriers Addressed

- Hydrogen Delivery I. Low cost, rugged, reliable dispensers
- Market Transformation B. High hydrogen fuel infrastructure capital costs
- Market Transformation F. Inadequate user experience for many hydrogen and fuel cell applications

## Partners

**National Renewable Energy Laboratory**

On-Road Fueling Research and Testing

Lead: Sam Sprik

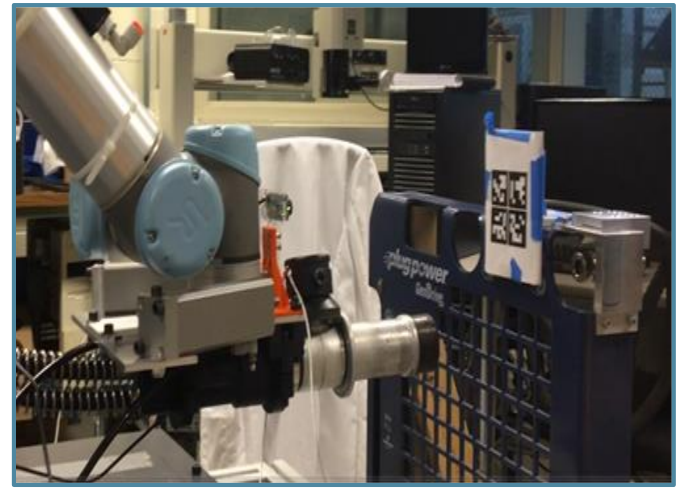
**Center for Future Energy Systems at Rensselaer Polytechnic Institute**

Vision System, Control Algorithms

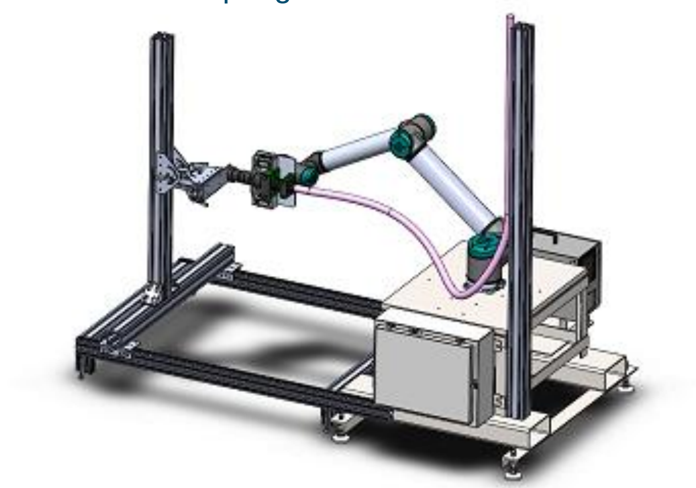
Lead: Stephen J. Rock, PhD

# Overview

- Budget Period 1 (2019-2020)
  - Design, assemble and test prototype fueling dispenser for Autonomous Guided Vehicles in a material handling application (primarily Rensselaer, Plug Power)
  - Research requirements and specifications for automotive fueling (primarily NREL)
- Budget Period 2 (2020-2021)
  - Design, assemble and test commercial-intent fueling dispenser for Autonomous Guided Vehicles in a material handling application. Testing to be performed at customer site for 16 weeks. (primarily Rensselaer, Plug Power)
  - Demonstrate capabilities needed to fuel on-road vehicles with off-the-shelf robot in a lab environment (primarily NREL)
- Budget Period 3 (2021-2022)
  - Design and demonstrate autonomous fueling of on-road hydrogen vehicle using off-the-shelf robot (Rensselaer, Plug Power, NREL)



Robot attempting connection to fuel cell mockup



Robotic assembly for NREL's laboratory test cell

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# Relevance

Goal is to develop automated fueling for both material handling and automotive fuel cell markets

- Automated fueling of on-road vehicles will allow fully autonomous operation of fuel cell vehicles
- There are advantages for non-autonomous vehicles as well:
  - Operator can be productive doing other tasks while fueling
  - Revenue source for hydrogen station stores
  - Convenience
  - Increased safety
- Market for material handling fuel cells is based on reducing labor costs for refueling. Automation reduces connection time, eliminates the need to train operators to refuel and reduces wear and tear on the infrastructure.

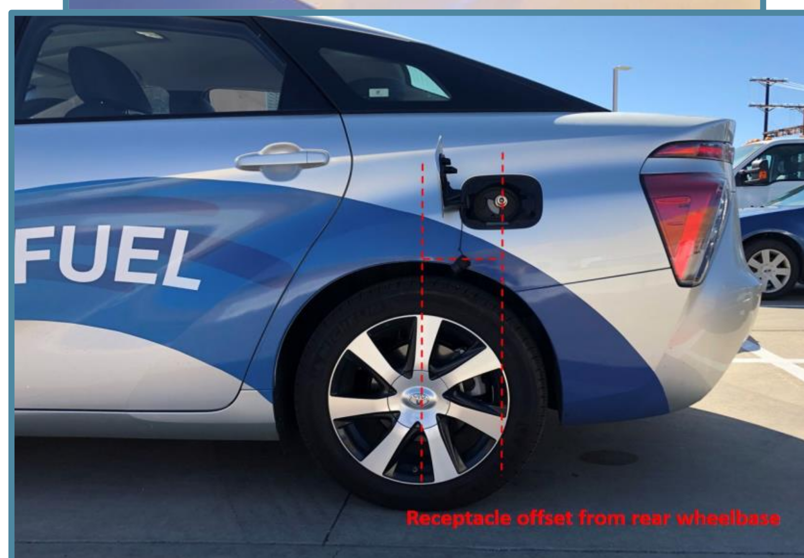
| Barrier | Impact |
|---|---|
| Hydrogen Delivery I. Low cost, rugged, reliable dispensers | Design automated dispenser using custom, low-cost robotics. Increase reliability through repeatable, carefully controlled connections. |
| Market Transformation B. High hydrogen fuel infrastructure capital costs | Offset capital costs of infrastructure by generating other forms of revenue (e.g. driver can spend more time in hydrogen station store), lower insurance costs by eliminating need for driver to fuel manually. |
| Market Transformation F. Inadequate user experience for many hydrogen and fuel cell applications | Eliminate need to train drivers to refuel, create improved experience vs combustion engines |

# Approach

Automated connection of a hydrogen filling nozzle to an on-road vehicle receptacle poses many challenges:

- Location of the receptacle is not standardized across vehicles
- No markings on vehicle dedicated to assist the vision system for finding the receptacle
- The fuel door must be opened somehow
- The dust cap must be removed
- Lighting/glare are not easily controlled outdoors
- Precipitation makes vision feedback less reliable
- Freezing temperatures/precipitation may cause nozzle to stick upon disconnect

**Many of these challenges do not exist in the indoor material handling application**

# Approach

PLUG POWER

Plug Power has more than 30,000 fuel cell systems operating in indoor material handling (forklift) applications. The team decided to leverage this controlled environment to simplify the design of the first automated dispenser. The advantages are:

- Indoor environment
- Control over location of receptacle
- Ability to add markings to assist vision system
- No fuel door
- Dust cap can be adapted to assist robot
- Lighting/glare are more consistent indoors
- No precipitation
- Non-freezing environment

Fueling receptacle location can be modified in future designs to accommodate automation

ArUco marker for vision system

GenDrive fuel cell unit front panel showing location of receptacle relative to ArUco marker

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# Approach

- Evaluation of off-the-shelf Class 1, Zone 2 robotic solutions proved cost-prohibitive for a commercial application.  A custom solution is needed.
- Several robotic architectures were considered.  The selected concept is a SCARA robot with a ball screw providing vertical movement.
- The prototype robotic dispenser will be located next to a standard indoor hydrogen dispenser.
  - Fill control and required valving is located in the standard dispenser
  - Hoses leading from the standard dispenser to the robotic arm supply hydrogen to the nozzle
  - The manual hydrogen dispenser can be used when the robotic dispenser is not in use

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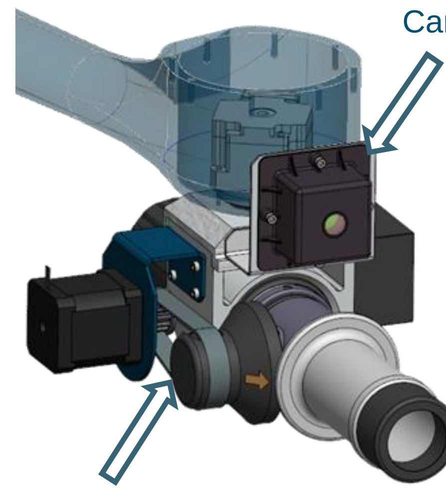
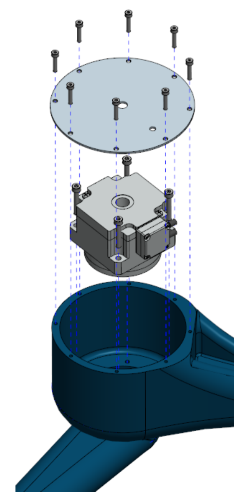
# Approach

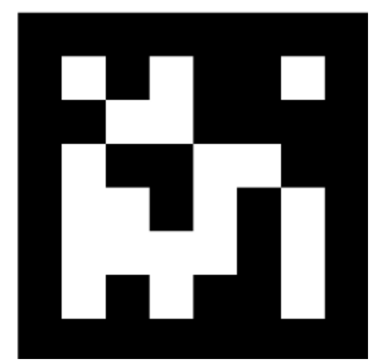
- Receptacle location is determined by a vision system and ArUco fiduciaries
  - Camera mounted on end effector provides images to computer mounted in base of dispenser
  - ArUco is placed on front panel of fuel cell unit at a specified position relative to receptacle
  - Receptacle location can be calculated from position of ArUco marker

- In order to achieve Class 1, Zone 2 compliance, motors are housed in housings pressurized with air to maintain unclassified environment around motor

- End effector contains wrist motor to allow rotation of nozzle about vertical axis





Motor Housing


ArUco Marker

# Approach

The team has selected the following as the relevant robotic/machinery standards.  The design is being evaluated against the applicable sections of these standards.

| Type of standard | Number of standard | Title of standard |
|---|---|---|
| **Type-A standard**<br>**Basic safety standards** | ISO 12100 | Safety of machinery – General principles of design – Risk assessment and risk reduction |
| **Type-B1 standard**<br>**Generic safety standards for specific safety aspects** | ISO 13854<br>IEC 60204-1<br>ISO 13849-1<br>ISO 13857<br>ISO 13855 | Minimum gaps to avoid crushing of parts of the human body<br>Electrical equipment of machines – Part 1: General requirements<br>Safety-related parts of control systems — Part 1: General principles for design<br>Safety distances to prevent hazard zones being reached by upper and lower limbs<br>Positioning of safeguards with respect to the approach speeds of parts of the human body |
| **Type-B2 standard**<br>**Generic safety standards for safeguards** | ISO 13850<br>IEC 61496-1<br>ISO 14119<br>ISO 14120 | Emergency stop function — Principles for design<br>Electro-sensitive protective equipment - Part 1: General requirements and tests<br>Interlocking devices associated with guards — Principles for design and selection<br>Guards — General requirements for the design and construction of fixed and movable guards |
| **Type-C standard**<br>**Machine safety standards (product standard)** | UL 1740<br>ANSI/RIA R15.06<br>ISO 10218-1<br>ISO 10218-2<br>RIA TR R15.306<br>RIA TR R15.406 | Robots and robotic equipment<br>Industrial robots and robot systems – safety requirements<br>Robots and robotic devices. Safety requirements for industrial robots.<br>Safety requirements for industrial robots - Part 2: Robot systems and integration<br>Industrial robots – task based risk assessment methodology<br>Industrial robots and robot systems – safety requirements. Safeguarding |
| | | |

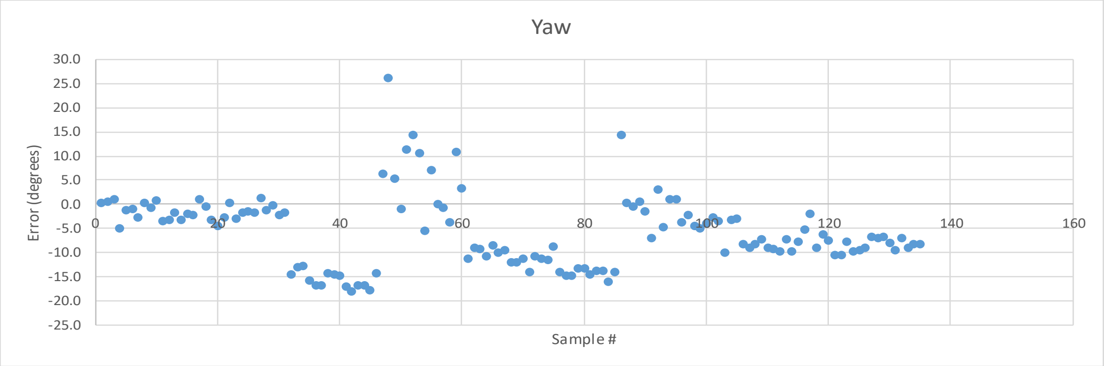
# Approach

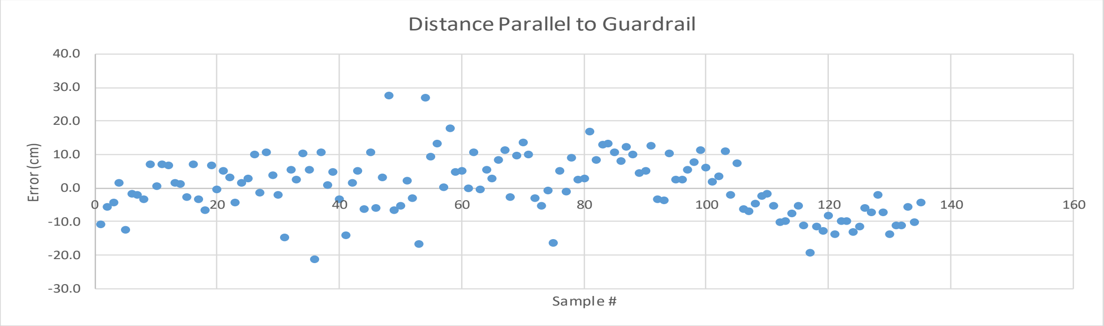
The team has made steady progress against the program goals for 2019/2020

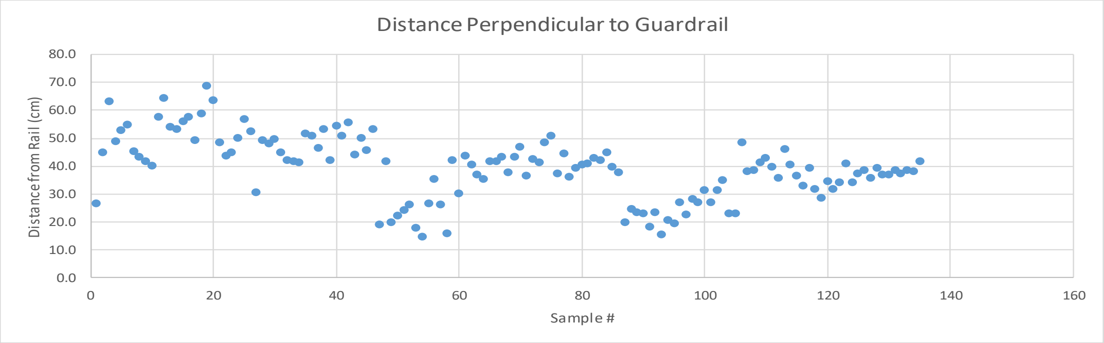
| Task | Milestone Description (Go/No-Go Decision Criteria) | Milestone Verification Process (What, How, Who, Where) | Status |
|---|---|---|---|
| Requirements Gathering | Deliver System Requirements Document to DOE | Review with DOE project manager | Complete.<br><br>Delivered to program manager 7/30/2019 |
| AGV Dispenser Requirements Alpha Concept Phase | Concept Design Review (Concepts for mechanical, electrical, controls and safety defined and selected) | Design Review with DOE project manager | Completed Dec 16, 2019 |
| Alpha AG Dispenser Design Review | Alpha Design Review (System process and instrumentation diagram, mechanical design, controls) | Design Review with DOE project manager and NREL | Completed Dec 16, 2019 |
| Alpha Unit Assembled | Alpha Unit Assembled | Prototype fully assembled and ready for debug | Expected July 2020 |
| Alpha Unit Testing | Alpha Unit Testing Complete (Perform minimum 200 connection/fueling attempts) | Video or first-hand observation by NREL/DOE project manager | Expected August 2020 |
| Automotive Dispenser Concept Complete | Concept Complete (Safety, codes and standards, operating requirements, time target assessments complete) | Review to be conducted with DOE project manager | Expected July, 2020 |
| Automotive Dispenser Specifications | Specification Complete (Specifications for beta unit sensors, actuators, communications complete) | Review to be conducted with DOE project manager | Expected July, 2020 |
| Go/No-Do Decision | Decision to proceed to Beta phase of AGV Dispenser. Alpha unit demonstrated 99% or better connection success rate and reduction in connection time of 20% versus a human operator over minimum 200 attempts. | Review with DOE project manager. Video or first-hand observation by NREL/DOE project manager | Expected August, 2020 |

# Accomplishments

- In order to determine the required operational envelope of the robotic arm, the team recorded the position of the fueling receptacle relative to the fuel dispenser in fuel cell-powered lift trucks over more than 100 trials
- The resulting data was compiled to determine the maximum reach/angles required of the robot
- The resulting design requirements dictate that the mechanism must be capable of:
  - 80 cm horizontal travel (parallel to face of dispenser)
  - 60 cm vertical travel
  - 80 cm depth travel (perpendicular to face of dispenser)
  - +/-20˚ nozzle rotation about the vertical axis

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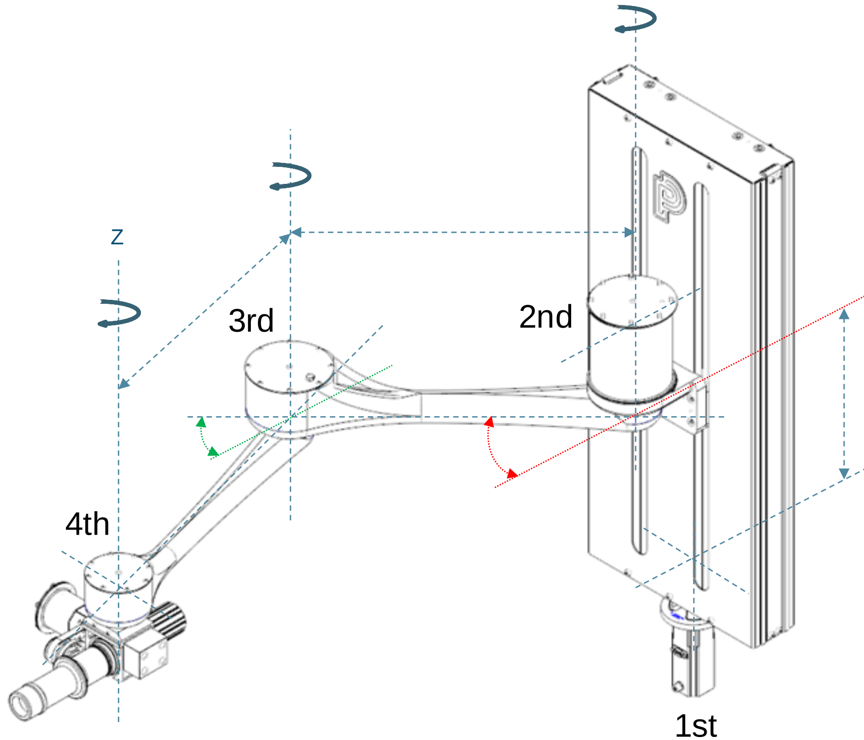
# Accomplishments

Four degree of freedom robotic arm design

- 1st Joint – Vertical travel
  - Ball screw mechanism with a maximum of 730mm of vertical travel
- 2nd Joint – Rotation – Robot reach
  - Largest motor with ~215° of available rotation
- 3rd Joint – Rotation – Robot reach
  - Medium motor with 360° of available rotation
- 4th Joint – Rotation – End effector yaw
  - Small motor with 360° of available rotation.



# Accomplishments

- Example of motor sizing: ball screw drive
  - Stepper motor with incremental encoder

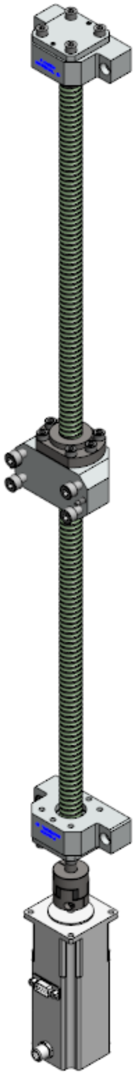
**Motor Specs**

| | | |
|---|---|---|
| Motor RPM | 1940 | rpm |
| Nominal Voltage | 48 | V |
| Nominal Current | 5 | A |
| Break Holding Torque | 1 | Nm |
| Motor Holding Torque | 1.4 | Nm |
| Permissible Axial shaft load | 10 | N |
| Permissible Radial shaft load | 52 | N |
| Step Angle | 1.8 | deg |
| Step Angle Tolerance | 5% | |
| Max Angle | 1.89 | deg |
| Min Angle | 1.71 | deg |

| | | |
|---|---|---|
| Steps per revolution | 200 | |
| Nominal per step | 0.0250 | mm |
| Max Distance per Step | 0.0263 | mm |
| Max Distance per Step | 0.0238 | mm |

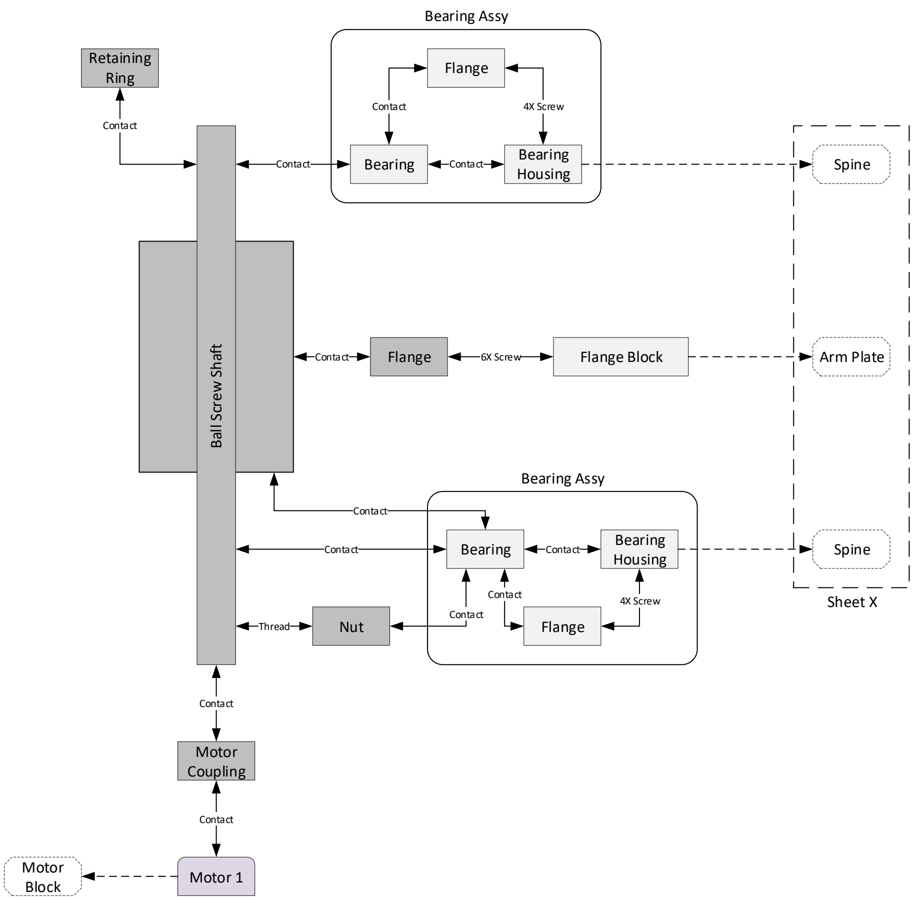
**Travel Speed:**

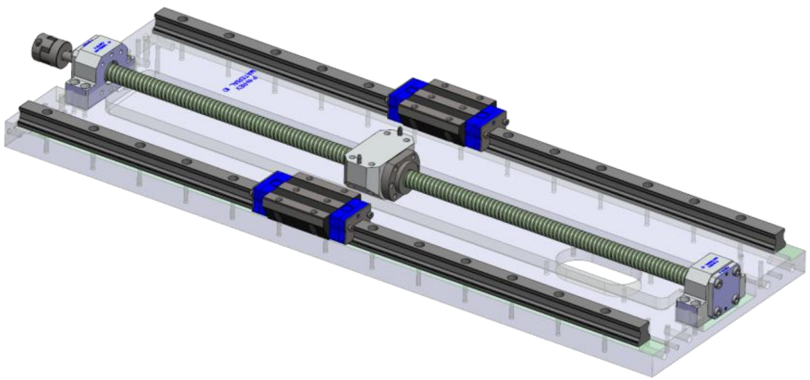
| | | | | | | |
|---|---|---|---|---|---|---|
| Motor RPM | 1940 | rpm | | | | |
| Travel Speed | 6.365 | in/sec | 0.1617 | m/s | 161.667 | mm/s |
| Acceleration Time | 0.1 | s | | | | |
| Acceleration | 1.617 | m/s^2 | | | | |
| | 4.70 | sec full travel | | | | |

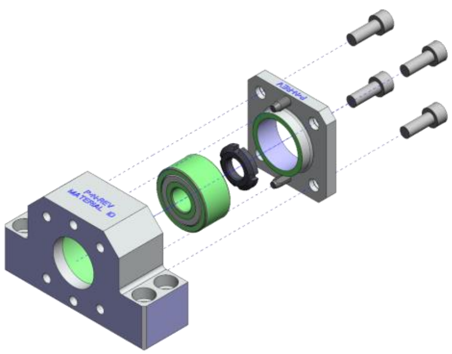


# Accomplishments

Ball screw design with sliders for vertical movement



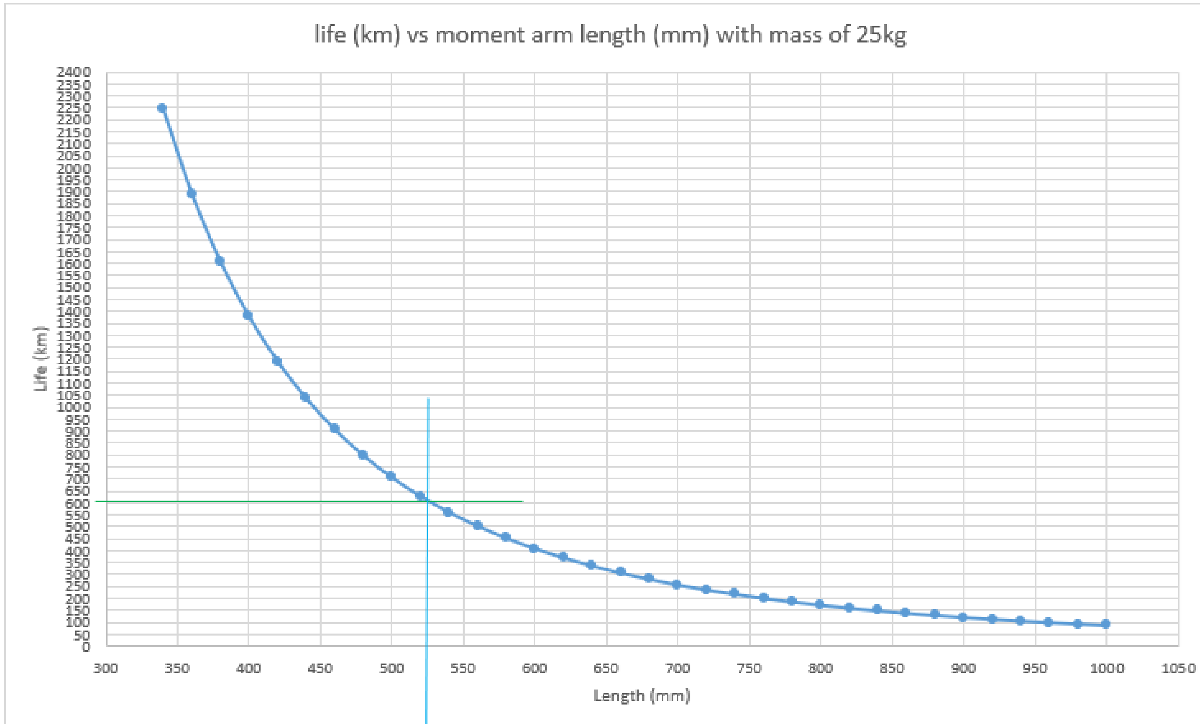



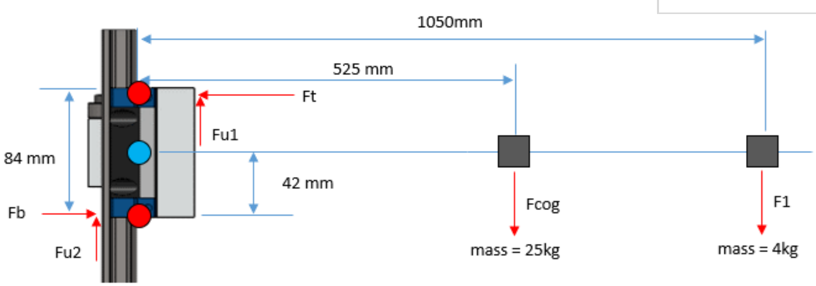


# Accomplishments

Ball screw carriage life analysis meets 15 year requirement for life

| | | |
|---|---|---|
| Fills per day | 100 | fills |
| Travel per fill | 730 | mm |
| Travel per day | 73000 | mm |
| Life requirement | 15 | years |
| Travel over life | 399.675 | km |



# Accomplishments

Inverse kinematics calculations ensure robotic arm speed does not rotate beyond acceptable safety limits

$L_1 := 525 \quad d_1 := 0 \quad \theta_1 := -45\text{deg} \quad v_x := 250 \quad t_a := 0.5$

$L_2 := 525 \quad d_2 := -52 \quad \theta_2 := 90\text{deg} \quad v_y := 250$

$L_3 := 0 \quad d_3 := -42 \quad \theta_3 := \theta_1 + \theta_2 = 45 \cdot \text{deg}$

$F_{max} := 20\text{lb}$

$a_x := \frac{v_x}{t_a} = 500$

$a_y := \frac{v_y}{t_a} = 500$

$v_z := 226 \frac{\text{mm}}{\text{s}} \quad t_z := 0.1\text{s}$

$a_z := \frac{v_z}{t_z} = 2.26 \frac{\text{m}}{\text{s}^2}$

$$T_{01} := \begin{pmatrix} \cos(\theta_1) & -\sin(\theta_1)\cdot 1 & \sin(\theta_1)\cdot 0 & L_1\cdot\cos(\theta_1) \\ \sin(\theta_1) & \cos(\theta_1)\cdot 1 & -\cos(\theta_1)\cdot 0 & L_1\cdot\sin(\theta_1) \\ 0 & 0 & 1 & d_1 \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 0.707 & 0.707 & 0 & 371.231 \\ -0.707 & 0.707 & 0 & -371.231 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$T_{12} := \begin{pmatrix} \cos(\theta_2) & -\sin(\theta_2)\cdot 1 & \sin(\theta_2)\cdot 0 & L_2\cdot\cos(\theta_2) \\ \sin(\theta_2) & \cos(\theta_2)\cdot 1 & -\cos(\theta_2)\cdot 0 & L_2\cdot\sin(\theta_2) \\ 0 & 0 & 1 & d_2 \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 525 \\ 0 & 0 & 1 & -52 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$T_{23} := \begin{pmatrix} \cos(\theta_3) & -\sin(\theta_3)\cdot 1 & \sin(\theta_3)\cdot 0 & L_3\cdot\cos(\theta_3) \\ \sin(\theta_3) & \cos(\theta_3)\cdot 1 & -\cos(\theta_3)\cdot 0 & L_3\cdot\sin(\theta_3) \\ 0 & 0 & 1 & d_3 \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 0.707 & -0.707 & 0 & 0 \\ 0.707 & 0.707 & 0 & 0 \\ 0 & 0 & 1 & -42 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$T_{02} := T_{01} \cdot T_{12} \cdot T_{23}$

$$\begin{pmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \end{pmatrix} := \begin{pmatrix} T02_{0,0} & T02_{0,1} & T02_{0,2} & T02_{0,3} \\ T02_{1,0} & T02_{1,1} & T02_{1,2} & T02_{1,3} \\ T02_{2,0} & T02_{2,1} & T02_{2,2} & T02_{2,3} \end{pmatrix} = \begin{pmatrix} 0 & -1 & 0 & 742.462 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & -94 \end{pmatrix}$$

$$\omega_x := \frac{v_x\cdot\cos(\theta_1+\theta_2) + v_y\cdot\sin(\theta_1+\theta_2)}{L_1\cdot\sin(\theta_2)} \rightarrow \frac{250\cdot\cos(45\cdot\text{deg}) + 250\cdot\sin(45\cdot\text{deg})}{525\cdot\sin(90\cdot\text{deg})} = 38.585\cdot\text{deg} \quad \text{deg/s}$$

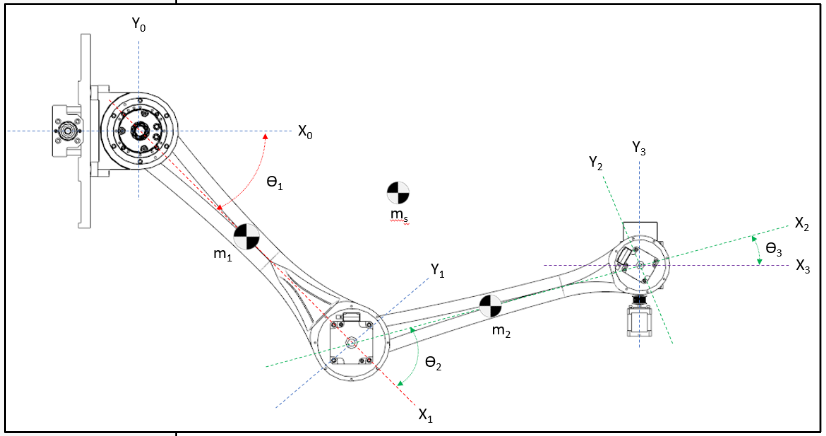
$$RPM_x := \frac{\omega_x \cdot \frac{180}{\pi}}{6} = 6.431\ \text{RPM}$$

$$\omega_y := \frac{-v_y\cdot(L_1\cdot\sin(\theta_1) + L_2\cdot\sin(\theta_1+\theta_2)) - v_x\cdot(L_1\cdot\cos(\theta_1) + L_2\cdot\cos(\theta_1+\theta_2))}{L_1\cdot L_2\cdot\sin(\theta_2)} \rightarrow -\frac{20\cdot\cos(45\cdot\text{deg})}{21\cdot\sin(90\cdot\text{deg})} = -38.585\ \text{deg/s}$$

$$RPM_y := \frac{\omega_y \cdot \frac{180}{\pi}}{6} = -6.431\ \text{RPM}$$

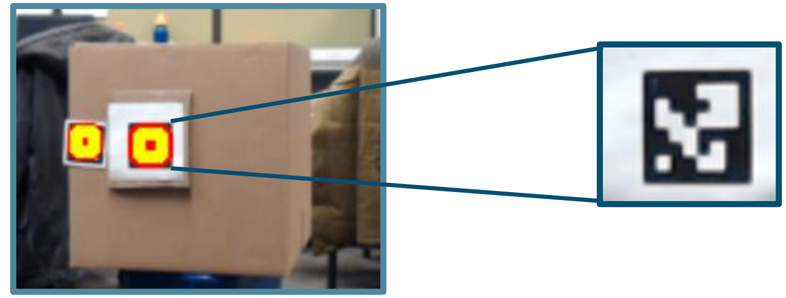
$$\alpha_1 := \frac{(-v_x\cdot\sin(\theta_1+\theta_2) + v_y\cdot\cos(\theta_1+\theta_2))\cdot(\omega_x+\omega_y) + (a_x\cdot\cos(\theta_1+\theta_2) + a_y\cdot\sin(\theta_1+\theta_2)) - L_1\cdot\cos(\theta_1)\cdot\omega_x\cdot\omega_y}{L_1\cdot\sin(\theta_1)} = -25.984\text{deg/s}^2$$

$$\alpha_2 := \frac{(a_y\cdot\sin(\theta_1) - a_x\cdot\cos(\theta_1))\cdot L_1 + (a_y\cdot\sin(\theta_1+\theta_2) + a_x\cdot\cos(\theta_1+\theta_2))\cdot L_2 + (v_y\cdot\cos(\theta_1) - v_x\cdot\sin(\theta_1))\cdot L_1\cdot\omega_x + (v_y\cdot\cos(\theta_1+\theta_2) + v_x\sin(\theta_1+\theta_2))\cdot L_2\cdot(\omega_x+\omega_y) + L_1\cdot L_2\cdot\cos(\theta_2)\cdot\omega_y^2}{L_1\cdot L_2\cdot\sin(\theta_2)} = 25.984\cdot\text{deg}$$



# Accomplishments

- Vision system is able to accurately detect and measure position of ArUco markers at distances of more than two meters using inexpensive webcam
- Averaging of the output of up to 20 filters is used to measure position under a wide array of lighting conditions



ArUco markers identified by vision system

| S | | | vec | | | |
|---|---|---|---|---|---|---|
| | X (in) +SDV | Y (in) +SDV | Z (in) +SDV | Pitch(d)+SDV | Yaw(d)+SDV | Roll(d)+SDV |
| 0- 0... 0/ 0 | | | | | | |
| 0- 1... 0/ 0 | | | | | | |
| 0- 2... 0/ 0 | | | | | | |
| 0- 3... 2/ 7 | 0.67 | 4.80 | 58.20 | 3.17 | −18.39 | 1.67 |
| 0- 4... 9/14 | 0.66 + 0 | 4.73 + 0 | 57.40 + 0.14 | 5.69 + 0.32 | −19.66 + 0.44 | 1.89 + 0.11 |
| 0- 5... 9/18 | 0.65 + 0 | 4.69 + 0 | 56.77 + 0 | 5.60 + 0.17 | −21.32 + 0.13 | 1.99 + 0.07 |
| 0- 6... 9/19 | 0.65 + 0 | 4.68 + 0 | 56.66 + 0 | 4.65 + 0.27 | −21.19 + 0.15 | 1.77 + 0.08 |
| 0- 7... 4/19 | 0.67 + 0 | 4.67 + 0 | 56.60 + 0 | 4.58 + 1.02 | −10.62 + 19.93 | 0.79 + 1.75 |
| 0- 8... 4/19 | 0.68 + 0 | 4.74 + 0.13 | 57.37 + 1.56 | 4.54 + 0.62 | −15.47 + 8.63 | 1.31 + 0.67 |
| 0- 9... 9/19 | 0.66 + 0 | 4.67 + 0 | 56.58 + 0 | 3.53 + 0.37 | −18.65 + 0.14 | 1.51 + 0.04 |
| 0-10... 9/19 | 0.65 + 0 | 4.63 + 0 | 56.13 + 0.15 | 4.21 + 0.35 | −18.98 + 0.47 | 1.84 + 0.09 |
| 0-11... 9/19 | 0.64 + 0 | 4.57 + 0 | 55.31 + 0 | 5.63 + 0.23 | −20.38 + 0.16 | 2.11 + 0.03 |
| 0-12... 9/19 | 0.65 + 0 | 4.56 + 0 | 55.20 + 0 | 4.80 + 0.26 | −19.82 + 0.08 | 1.95 + 0.05 |
| 0-13... 9/19 | 0.65 + 0 | 4.54 + 0 | 55.06 + 0 | 4.09 + 0.34 | −19.79 + 0.15 | 1.64 + 0.06 |
| 0-14... 9/19 | 0.65 + 0 | 4.54 + 0 | 55.03 + 0 | 4.89 + 0 | −19.26 + 0 | 1.57 + 0 |
| 0-15... 9/19 | 0.67 + 0 | 4.54 + 0 | 55.05 + 0 | 5.21 + 0.11 | 13.61 + 12.33 | −1.34 + 1.07 |
| 0-16... 9/19 | 0.65 + 0 | 4.52 + 0 | 54.75 + 0.16 | 4.19 + 0.39 | −19.92 + 0.53 | 1.49 + 0.13 |
| 0-17... 9/19 | 0.63 + 0 | 4.48 + 0 | 54.08 + 0 | 4.47 + 0.12 | −20.77 + 0.16 | 2.14 + 0.04 |
| 0-18... 9/19 | 0.63 + 0 | 4.45 + 0 | 53.87 + 0 | 5.35 + 0.18 | −20.30 + 0.14 | 2.20 + 0.07 |
| 0-19... 9/19 | 0.65 + 0 | 4.56 + 0 | 55.17 + 0 | 5.95 + 0.17 | −18.84 + 0.09 | 1.84 + 0.05 |
| 0-20... 9/19 | 0.65 + 0 | 4.55 + 0 | 55.15 + 0 | 5.73 + 0.13 | −18.84 + 0.10 | 1.80 + 0.06 |

Output of vision system filters

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# Responses to Previous Reviewer Comments

This project was not reviewed last year

# Collaborations

| Partner | Project Roles |
|---|---|
| Plug Power | Prime; management and coordination; mechanical design of dispenser; vision system; safety analysis; installation, testing and operation at commercial site |
| Center for Future Energy Systems at Rensselaer Polytechnic Institute | Subrecipient; vision system; mechanical analysis; programming for automotive testing in Phase 3 |
| National Renewable Energy Laboratory | National Lab Partner; requirements and testing for automotive dispensing |

# Remaining Challenges and Barriers

- Construction and testing of robotic arm and vision system feedback
- Validation of air purging scheme to achieve unclassified zone around motors
- Implementation of safety system to prevent arm from inadvertently contacting operator
- Demonstration of positioning accuracy and stability to make reliable connection repeatedly
- Demonstration of technology in a real commercial environment (Budget Period 2)
- Reliable connection to on-road vehicles in outdoor environment (Budget Period 3)

# Proposed Future Work

Remainder FY2020

**Material Handling Dispenser Work**

- Assemble and test prototype dispenser.  Demonstrate 99% or better connection success rate and reduction in connection time of 20% versus a human operator over minimum 200 attempts
- Begin design of commercial dispenser for demonstration in 2021

**Automotive Dispenser Work**

- Complete automotive requirements

FY2021

**Material Handling Dispenser Work**

- Assemble and test dispenser for customer trial.
- Complete customer trial: (unit availability > 80%, connection success rate 95% or better and reduction in connection time of 20% versus a human operator over minimum 100 attempts)

**Automotive Dispenser Work**

- Assemble and test robot at NREL to experiment with automotive refueling

Any proposed future work is subject to change based on funding levels

# Summary

- Mechanical design of robotic dispensing system for material handling fuel cell vehicles is complete. Parts are on order and assembly is expected to be complete in July 2020.
- Design consists of custom SCARA design with ball screw for vertical travel. Motors on end effector allow rotation of nozzle about vertical axis and actuation of locking mechanism. Location of fueling receptacle is determined relative to ArUco marker positions measured by vision system. Camera mounted on end effector provides images to computer.
- Safety and adherence to codes and standards are a focus of the design.
- Automotive fueling is a more challenging task due to the outdoor environment and lack of receptacle location standards. Team is working on the requirements for this application for use in future work.
- The three organizations (Plug, NREL and Rensselaer) have collaborated well together. The skillsets of the teams complement each other.

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