Autonomous Hydrogen Fueling Station

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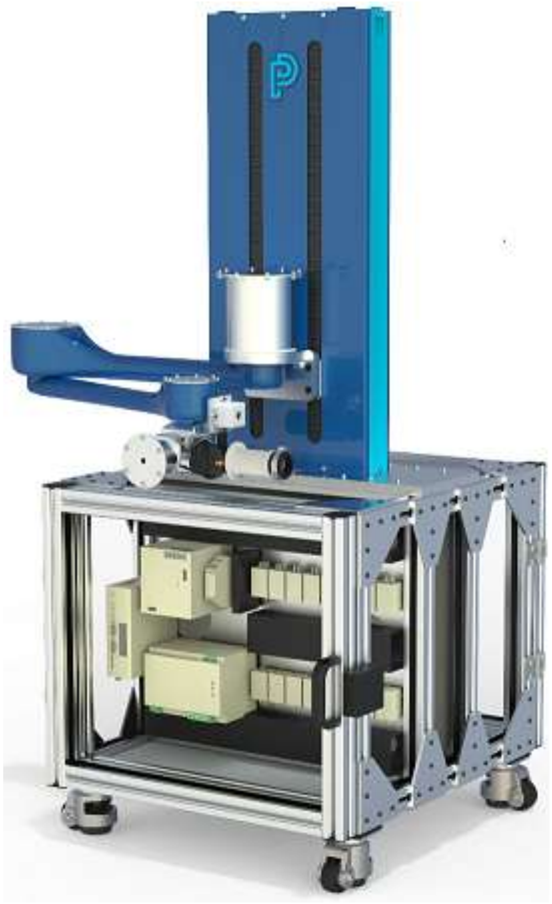
DOE Hydrogen Program
2024 Annual Merit Review
and Peer Evaluation Meeting

AMR Project ID TA029

Project Goals

Objective 1: Develop a commercial automated hydrogen dispenser for the material handling fuel cell market with a connection success rate of at least 95% in a warehouse environment. The dispenser shall achieve a reduction in connection time of 20% versus a human operator and enable use of fuel cell-powered autonomous guided vehicles that can operate round the clock with no human intervention.



Objective 2 : Research the requirements for automated fueling of on-road vehicles and demonstrate fueling of a vehicle with a connection success rate of 95% using a modified off-the-shelf robot. This work shall demonstrate the viability of fully autonomous fuel cell electric vehicles.

Overview

Timeline

Project Start Date: Oct 2018
Award Received: Mar 2019
(work started at this time)
Phase 1 End Date: Sep 2024*
Phase 2 and 3: TBD
*Proposed. 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:	$616,187*
Total Cost Share Funds Spent:	$207,266*

*as of 12/31/2024

Barriers Addressed

- Hydrogen Delivery: Low cost, rugged, reliable dispensers
- Hydrogen Delivery: Hydrogen refueling for automated vehicles (on road and industrial)
- Market Transformation: High hydrogen fuel infrastructure capital costs

Partners

Plug Power

Fuel Cell, Hydrogen infrastructure company

National Renewable Energy Laboratory

On-Road Fueling Research and Testing

Vecna Robotics

Vision System, Motion Control Algorithms

Mekable

Vision system, Motion Control Algorithms

Potential Impact

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.

The 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.

- Automated material handling fuel cells is also a market for an autonomous fueler, eliminating the need for human intervention on these automated material handling robots.

Future use of liquid hydrogen could be another benefit of this technology, enabling safer fills of liquid hydrogen.

Barrier	Impact
Hydrogen Delivery: Low cost, rugged, reliable dispensers	Design automated dispenser using custom, low-cost robotics. Increase reliability through repeatable, carefully controlled connections.
Hydrogen Delivery: Hydrogen refueling for automated vehicles	Enable fully autonomous hydrogen fuel cell material handling and autonomous on / off road vehicles
Market Transformation: Inadequate user experience for many hydrogen and fuel cell applications	Eliminate the need to train drivers to refuel, create improved experience vs combustion engines

Approach

Budget Period 1 (2019-2024)

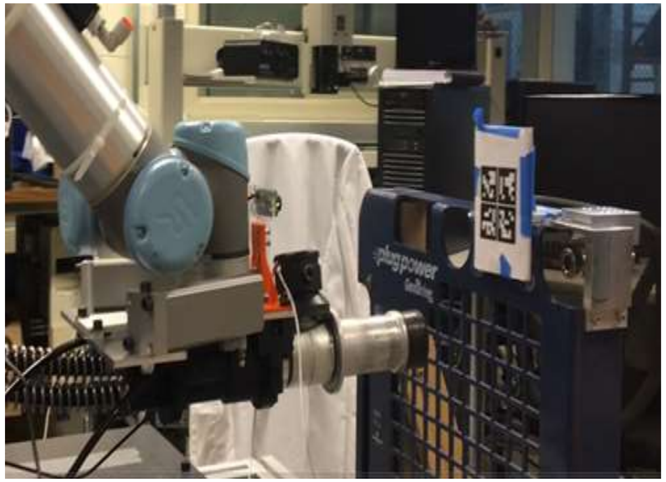
- Design, assemble, and test prototype fueling dispenser for Autonomous Guided Vehicles in a material handling applications (Plug Power, Vecna, Mekable)
- Research requirements and specifications for automotive fueling (primarily NREL)

Budget Period 2 (TBD)

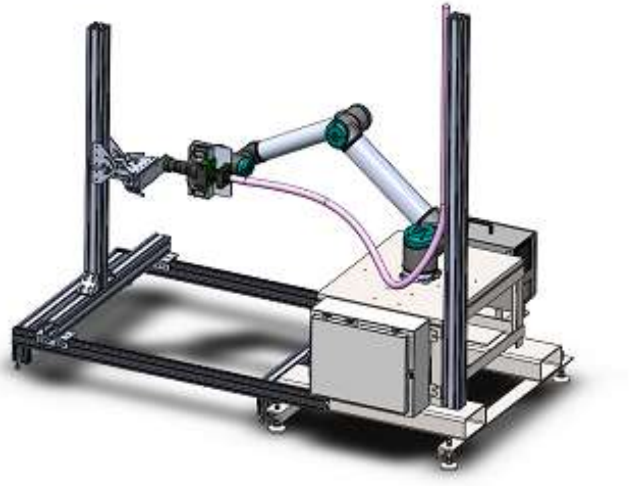
- Design, assemble, and test commercial-intent fueling dispenser for Autonomous Guided Vehicles in a material handling application. Testing to be performed at customer site for 16 weeks. (Plug Power, ??)
- Demonstrate capabilities needed to fuel on-road vehicles with off-the-shelf robot in a lab environment (Commercial options exist)

Budget Period 3 (TBD)

- Design and demonstrate autonomous fueling of on-road hydrogen vehicle using off-the-shelf robot (Commercial options exist)



Robot attempting connection to fuel cell mockup



Robotic assembly for NREL’s laboratory test cell

Approach

Plug Power has more than 35,000 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 the location of the receptacle

Ability to add markings to assist the vision system

No fuel door

Dust cap can be adapted to assist the 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

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 manual indoor hydrogen dispenser.

- Fill control and required valving are located in the manual dispenser.
- Hoses leading from the manual dispenser to the robotic arm supply hydrogen to the nozzle.
- The manual dispenser can be used when the robotic dispenser is not in use.

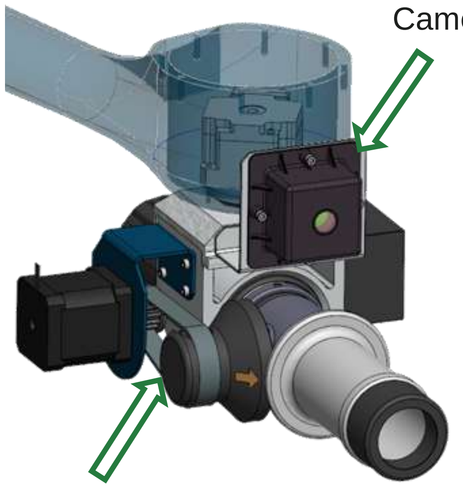
Approach

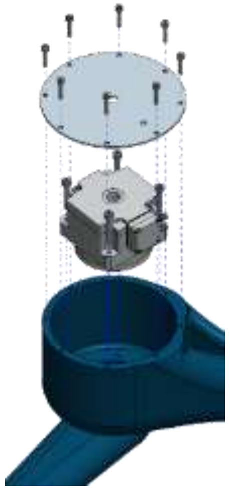
Receptacle location is determined by a vision system and ArUco fiduciaries.

- 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.

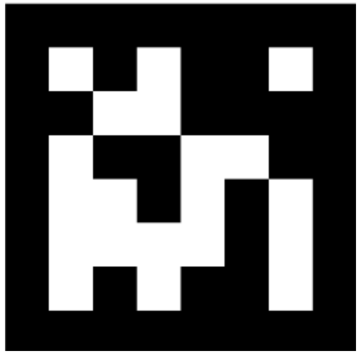
In order to achieve Class 1, Zone 2 compliance, motors are housed in housings pressurized with air to maintain unclassified environment around motor.

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





Motor Housing



ArUco Marker

Safety Planning and Culture

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

Safety Planning and Culture

- Robot was reviewed with Plug EHS and positive air pressure was added to all electrical cabinets in 2021.
- Once program was restarted in 2024, it was reviewed with Plug EHS again.
  - EHS pointed a few challenges to autonomous H2 filling.
    - Robot Safety
    - H2 Safety
    - Material handler drive away before removal of nozzle
  - This program answers these issues for the prototype, but more work would need to be done for a production intent system.
    - The robot will be guarded with a fence to prevent workers from being nearby while filling.
      - During initial trials an autonomous pallet jack was used to eliminate any humans in the operating area.
    - The electronics of the robot are positively pressurized with air to prevent H2 near the motors and controllers.
    - The fuel cell will only be moved away once the robot returns home
      - For a production intent system the nozzle needs to be able to break away from the robot in case of a drive away.
      - For the prototype system the driver must stand at the fuel dispensing station for H2 to be dispensed. Human will be out of range of the robot and material handling equipment until the fill is finished. The dispenser shuts down if the human steps off of the dispenser pressure pad.

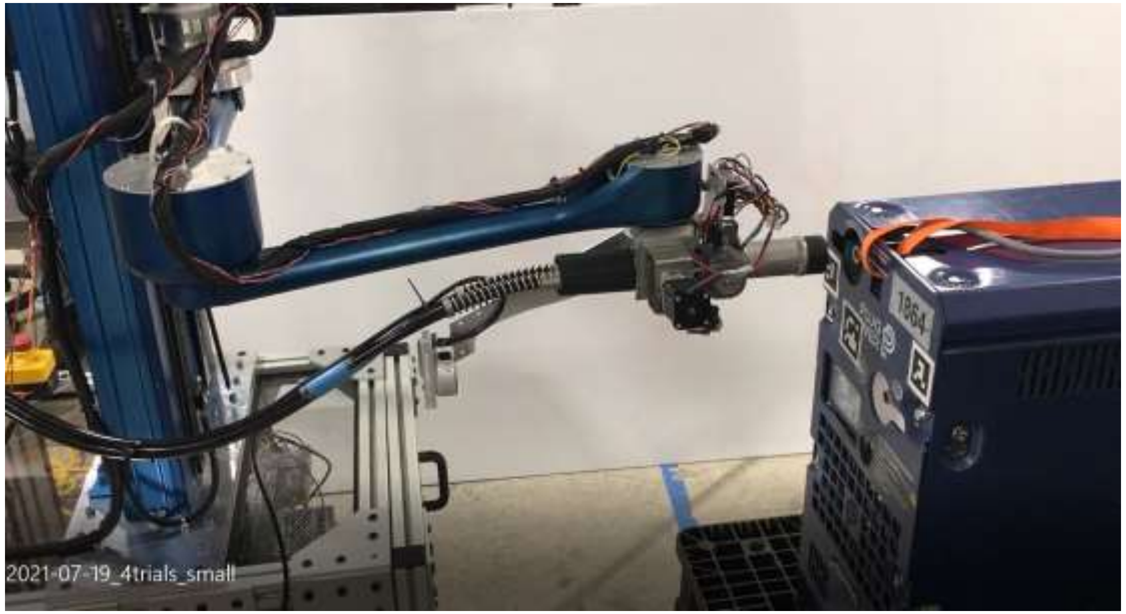
Accomplishments and Progress

- Work on the program paused in 2021 due to personnel leaving Plug and pandemic related worker limitations.
- Prior to this stoppage Vecna performed multiple connection / disconnections before shipping to Plug.
- Plug implemented hydrogen purge on the arm and electronics.
- Program work restarted in 2023.
- Q1 of 2024
    - New PI chosen.
    - Storage of robotic arm caused damage to the robot.
    - Arm refurbished in March 2024.
    - 200 dry connection / disconnections and real hydrogen fill planned for April 2024.
    - Current commercial robotic refilling stations investigated
        - AutoFuel, Rocsys, Mekable, and Fuelmatics contacted to inquire about commercially available refilling robots

Accomplishments and Progress

Vecna Robotics Controls Work

- Plug partnered with Vecna Robotics in 2021 for controls of the robotic arm
- ArUco QR codes applied to front of unit for easy robot visibility
- New camera and Lidar sensor was used with an arm extension for better positional accuracy in all lighting conditions
- Vecna showed successful connection and disconnection to a fuel cell
- Vecna completed 199 connections to the fuel cell
- Vecna shipped the robot to Plug Power for final integration work



Accomplishments and Progress

- Robot at Plug
  - Vecna successfully shipped robot to Plug.
  - Plug performed sealing of electronics box and robotic arm.
  - Purge air system was added to robotic arm and controls cabinet
  - During sealing work and final storage some electrical cables were damaged
  - Electrical debug / rewiring done by Plug and Mekable (New company with prior Vecna Robotics employees)

Accomplishments and Progress

The motors are all in positive air pressure chambers

Enclosed elbow stepper motor

Vertical travel stage

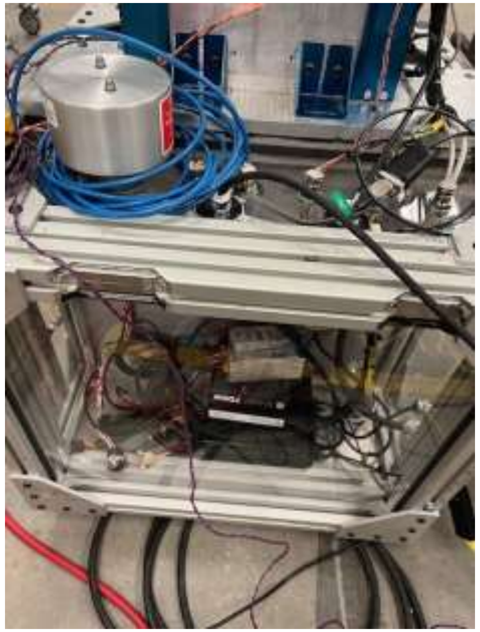
Enclosed shoulder stepper motor

Enclosed wrist stepper motor

Air pressure safety switch

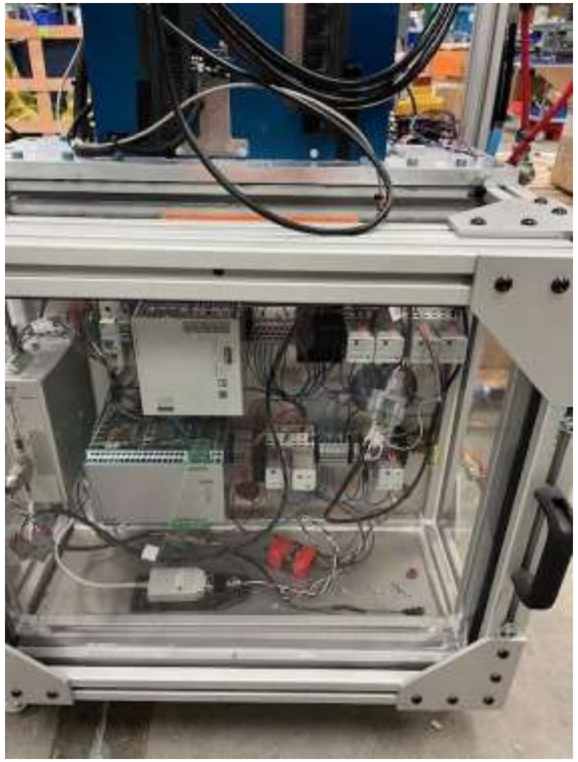
Enclosed valve motor

Accomplishments and Progress



Mini-computer compartment
-positive air pressure

Motor controller and safety relay
compartment-positive air pressure



Computer interface
with remote e-stop

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

- This project was not reviewed in the previous year's AMR

Collaboration and Coordination

- **Plug Power**
- Fuel Cell, Hydrogen infrastructure company

- **National Renewable Energy Laboratory**
  - On-Road Fueling Research and Testing
  - Work reviewed in 2021 AMR

- **Vecna Robotics**
  - Vision System, Motion Control Algorithms
  - Work completed in 2021

- **Mekable**
  - Vision system, Motion Control Algorithms
  - Continued work from Vecna Robotics

Remaining Challenges and Barriers

- Operational testing of the robot still needs to be conducted with active Plug Power fuel cells.
  - Plug Power's systems currently require 3 hookups for refill for material handling: H2, data, and water removal.
  - H2 and data can be handled with newer H2 receptacles.
  - Water removal will always be a separate nozzle for indoor material handling applications.
  - Robotic arm could feature both nozzles, but Plug's fuel cells would need standardized locations for H2 and water nozzles.
- QR codes used for positioning can be damaged or obscured and need to be placed accurately to the nozzle.
  - Robotic vision systems have advanced significantly since the project started.
    - Companies like Autofuel and Rocksys have robotic systems that can recognize the electrical or gasoline connections on vehicle and position the filler appropriately.
    - Newer cobot robotic arms are safer for operation around humans and cheaper than in 2019.
- Business case for autonomous refueling still not assured.
  - Autonomous material handling and autonomous on / off road vehicles are not widespread.
  - Current costs versus manual labor not a significant savings.

Proposed Future Work

- Any proposed future work is subject to change based on funding levels.
- Plug will undergo a survey of the autonomous refueller market to evaluate current market leaders in the space.
- Plug will evaluate costs of adapting current available market leaders to H2 and material handling
- Plug will evaluate the business case for autonomous refueling in relation to material handling

Summary

- Autonomous refueler was last reviewed in 2021’s AMR
- In 2021 Vecna Robotics completed initial programming work of the robot and completed many test connections autonomously
- In 2023 Plug restarted the program with a new PI and new team
  - The robot was recovered from storage and returned to working form
  - The robot completed the dry and H_2 connection goals in April of 2024
- In the intervening time the robotics industry has advanced significantly with human safe robots and robotic vision.
- New evaluations of commercially available robotic systems need to be reviewed for potential phase 2 plans.