ARM SMART COMPANION ROBOT PROJECT

Phase I : March 15, 2018 – March 15, 2019

Presented at ACC 2019 Workshop
Robot Assisted Manufacturing: Challenges and Opportunities
Tuesday July 9

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CU-ICAR *Connected Autonomy* Systems

Manufacturing Deployments: Scale and Complexity

Scale

Complexity

Small Scale (Created)

Mid Scale COTS

Full Scale COTS

Heavy-payload assist
Human following

YouBot

Baxter+Ridgeback

ABB YuMi +Ridgeback

Transbotics AGV

Smart Companion Robot
Version 1.a Proof of Concept

Yaskawa YMR12

Other Manufacturing Robotics/Automation Activities

(Collaborations: Dr. Yunyi Jia, Dr. Bing Li, Dr. Venkat Krovi, Dr. Matthias Schmid)

Collaborative Robotic Vacuum (CoRV)

Before:

Manual

New process:

Simulated

Collaborative
Automated

Collaborative Smart Companion Robot

Before:

Manual

New process:

Collaborative
Heavy-payload assist
Human following

CLEMSON

Collaborative HATCH SEAL Project

Before:

Manual

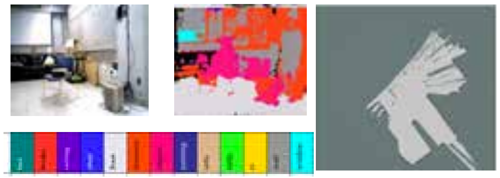
New process:

Collaborative Robot-Assisted

CU-ICAR *Connected Autonomy* Systems

Core Technologies

Semantic SLAM (Sensor enhanced Situational Awareness)



Human Machine Interfaces
(Haptics, AR, VR)

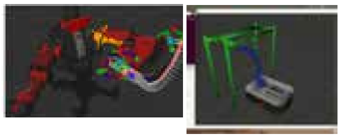
Video-based Human Activity Recognition

Middleware Frameworks

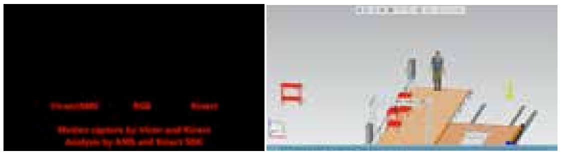
ROS NVIDIA TensorFlow QNX MathWorks

Advanced Wireless Networking

Simulation and Augmented Reality



Human Data Capture & Digital Human Modeling



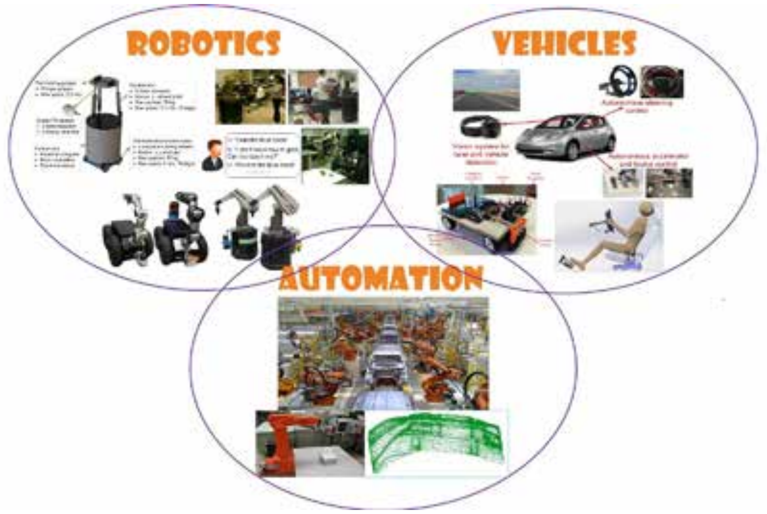
CU-ICAR *Connected Autonomy* Systems

People

Venkat Krovi

Pierluigi Pisu

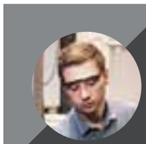
Bing Li



Yunyi Jia

Beshah Ayalew

Matthias Schmid



Clemson: Breadth and Depth of Offering

Cross Disciplinary Expertise

Model Based Systems Engineering	Advanced Planning, Control & Operations	Materials Innovation: Composites & Lightweighting	Robotics, Sensors, Wearables and IOT	Autonomous Systems	Intelligent Systems Integration & AI	Supply Chain and Optimization	Digital Thread
Dr. Philip Brown	Dr. Beshah Ayalew	Dr. Raj Bordia	Dr. Rebecca Hartley	Dr. Yunyi Jia	Dr. Amy Apon	Dr. Bill Ferrell	Dr. Amy Apon
Dr. Srikanth Pilla	Dr. Rae Cho	Dr. Hongseok Choi	Dr. Yunyi Jia	Dr. Venkat Krovi	Dr. Johnell Brooks	Dr. Mary Kurz	Dr. Kapil Madathil
Dr. Jianhua Tong	Dr. Sarah Harcum	Dr. Stephen Foulger	Dr. Gautam Koley	Dr. Laine Mears	Dr. James Martin	Dr. Scott Mason	Dr. Venkat Krovi
Dr. Chris Paredis	Dr. Laine Mears	Dr. Srikanth Pilla	Dr. Venkat Krovi	Dr. Josh Summers	Dr. Greg Mocko	Dr. Chris Paredis	Dr. Laine Mears
	Dr. Cole Smith	Dr. Fadi Abu-Farha	Dr. Kapil Madathil	Dr. Yue Wang	Dr. Chris Paredis		Dr. Melissa Smith
	Dr. Josh Summers		Dr. Sophie Wang	Dr. Matthias Schmid	Dr. Pierluigi Pisu		Dr. Josh Summers

MOTIVATION

Challenge in automotive assembly: Variability and volume

- Personalization and customer experience top trends driving the market (Forbes)
- BMW – 10^{13} possible product configurations per model
- Premium customers are very discerning!
  - Product without defects
  - Functionality and finish to exceed exectations
  - Time quality: custom-made and on-demand.

Img Src: Google Images

NEED FOR COGNITIVE & PHYSICAL ASSIST

MOTIVATION

Operations perspective:

- Automotive final assembly requires a person to build the customer-specific vehicle
- Understand the operation to be carried out the respective vehicle,
- Pick the appropriate parts
- Assemble them to the vehicle using a variety of processes (fastener bolts, clips, adhesives, …) and tools
- Conduct quality check on the operation

Strategic Perspective:

Automotive final assembly is handling most variability

- Mostly manual implementation (affects throughput & quality)
- Fenced industrial robots (are inflexible and expensive)
- Emerging collaborative robot use (Industrialization Evaluation needed)
- High volume/High Mix (business evaluation needs use-cases)

Img Src: BMW Manufacturing

TORSION BAR ASSEMBLY USE CASE

SUPPORT WITH OVERHEAD ASSEMBLY: HOLD / FASTEN / INSPECT.

Video(s) of the actual task on the shopfloor

Even in these two videos we can see the variability in task performance each time the task is done

Demonstration with an overhead fixture, navigation through static obstacles

Benefits Sought (ranked):
Ergonomics, product quality, productivity/headcount

Demo 1: TORSION BAR ASSEMBLY USE CASE

SUPPORT WITH OVERHEAD ASSEMBLY: HOLD / FASTEN / INSPECT. (4X Speed)

Smart Companion Robot

Version 1.a Proof of Concept

Clemson University - International Center for Automotive Research
June 2018

Img Src: BMW Manufacturing

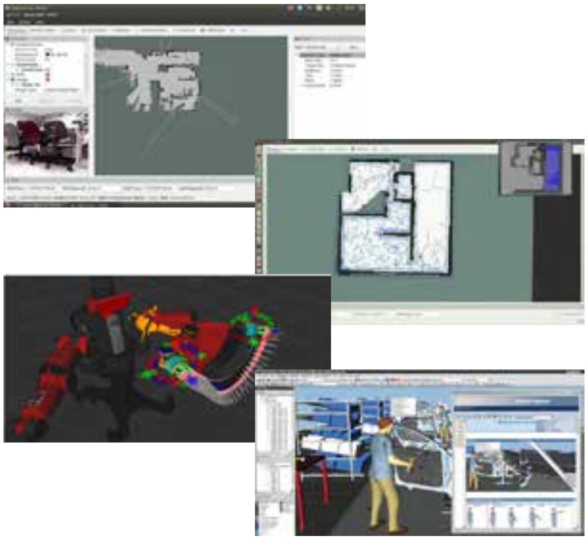
Torsion-bar overhead assembly use-case scenario

Demonstration with an overhead fixture, navigation through static obstacles

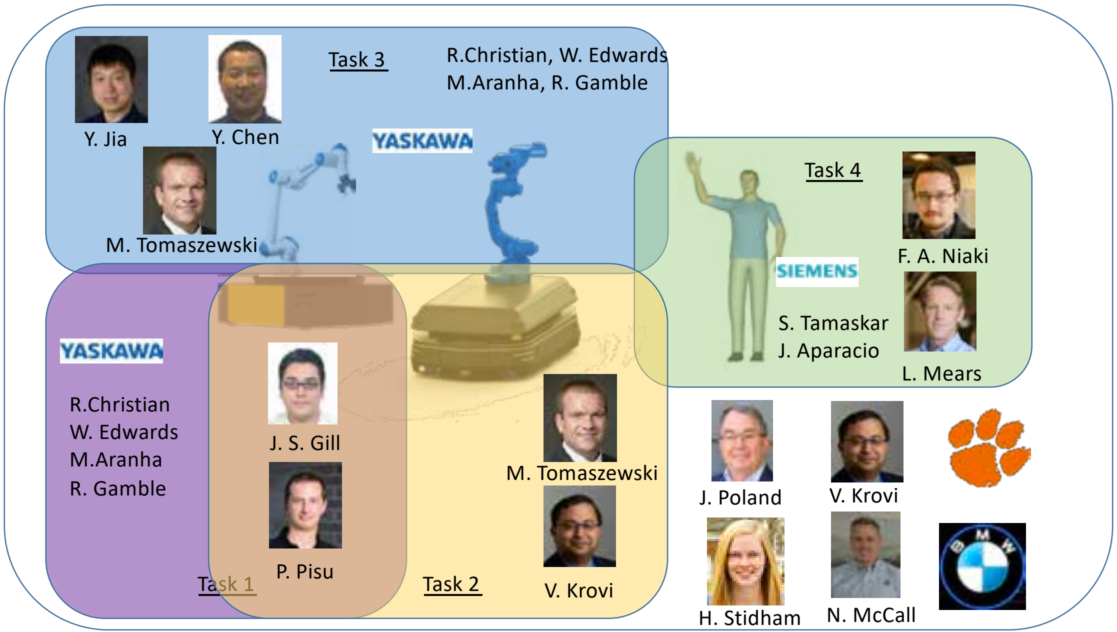
Benefits (ranked):
Ergonomics, product quality, productivity/headcount

Core Tasks 1-4

- T1: Situational awareness
  - Mapping of assembly-line dynamic environment
- T2: Mobile Base Planning and Control
  - Navigation to the part shelf and assembly station
- T3: Manipulator Planning and Control
  - Cognition of parts and physical assist
- T4: Digital Twin
  - Human factors and ergonomic analysis



Team Roles



Task 3

R.Christian, W. Edwards
M.Aranha, R. Gamble

Y. Jia
Y. Chen
M. Tomaszewski

Task 4

F. A. Niaki
S. Tamaskar
J. Aparacio
L. Mears

R.Christian
W. Edwards
M.Aranha
R. Gamble

J. S. Gill
P. Pisu
Task 1

M. Tomaszewski
V. Krovi
Task 2

J. Poland
V. Krovi
H. Stidham
N. McCall

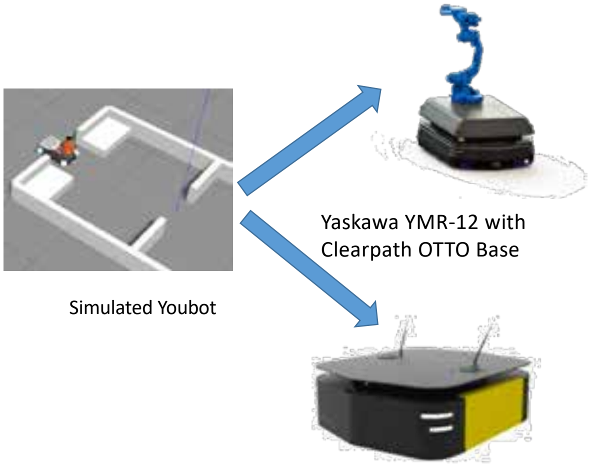
Situational Awareness, Mobile Base Motion Planning & Control

Objectives

Generating mobile base trajectories between the part shelf and the assembly station in an automotive assembly environment

Challenges

- Localizing in a changing environment
- Navigating through obstacles (static)
- Providing consistent results
- Transition from simulation to HIL system



Simulated Youbot

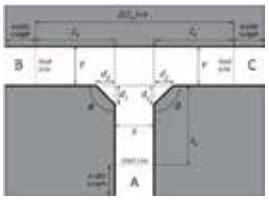
Yaskawa YMR-12 with Clearpath OTTO Base

Clearpath Ridgeback

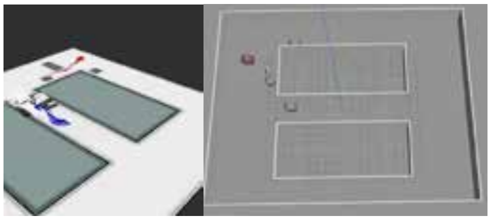
Situational Awareness and Navigation - Approach

Youbot

Fetch by fetchRobotics



Q1. Simulation environment setup, benchmarking review



Q2. Exploring different SLAM and ROS navigation algorithms (gmapping, hector, cartographer)

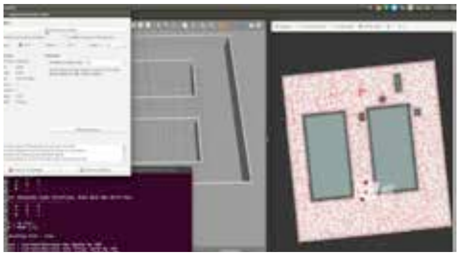
Yaskawa YMR-12 with Clearpath OTTO Base

Clearpath Ridgeback

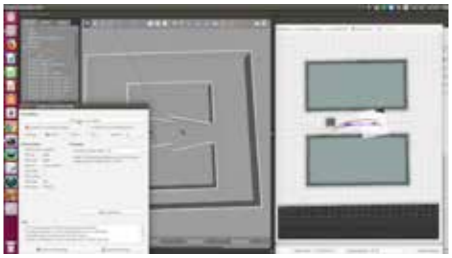
Q3. Evaluating the robots – YMR12 and Ridgeback

Q4. Optimizing the robot for consistency and obstacle avoidance

SLAM using offline ROS processing (replayed from LiDAR rosbags of manually driven YMR12)



Mobile Base Motion Planning and Localization in a NIST-rated Benchmark Course with Obstacles



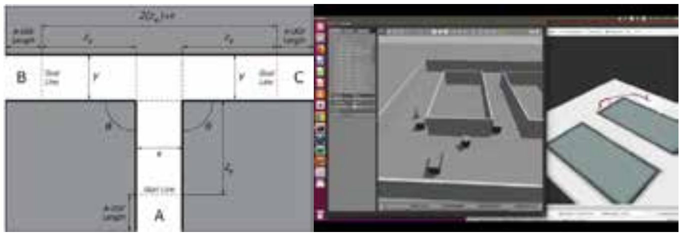
Correction of robot's belief after map updating in a changed environment

Experimental Results Validate Timing Inconsistencies

Assembly Environment – Need for Long Term Autonomy

Challenges in assembly environment

- Operation with humans
- Navigating through unstructured environment
- Time sensitive
- Extended operating times



ASTM standard F3244-17 reference test area designed in Gazebo

Recommended metric for navigation[*]:

- Mission success
- number of collisions
- robustness in navigation through narrow passages
- precision at target
- accuracy of goal achievement
- repeatability in accuracy
- path length
- time to collision
- execution time

The focus on these evaluations have primarily been accomplishment of missions without failures as well as safe operations.

Time consistency in execution has been ignored so far

ASTM standard used to provide a reference for a benchmarking arena

*C. Sprunk *et al.*, "An experimental protocol for benchmarking robotic indoor navigation," in *Experimental Robotics*, 2016, pp. 487–504.
W. Nowak, A. Zakharov, S. Blumenthal, and E. Prassler, "Benchmarks for mobile manipulation and robust obstacle avoidance and navigation," *BRICs Deliv. D*, vol. 3, p. 1, 2010.
R. Bostelman, T. Hong, and J. Marvel, "Survey of research for performance measurement of mobile manipulators," *J. Res. Natl. Inst. Stand. Technol.*, vol. 121, pp. 342–366, 2016.

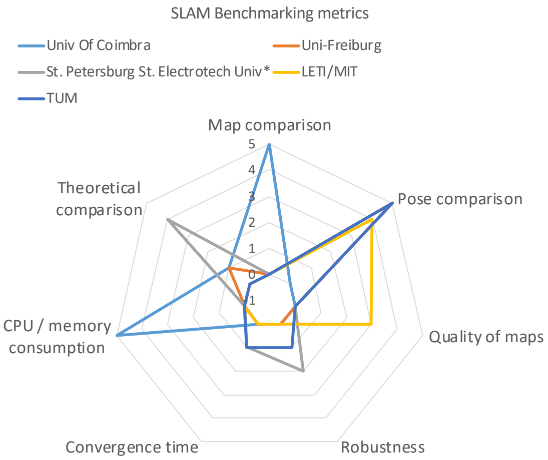
Assembly Environment – Need for Long Term Autonomy

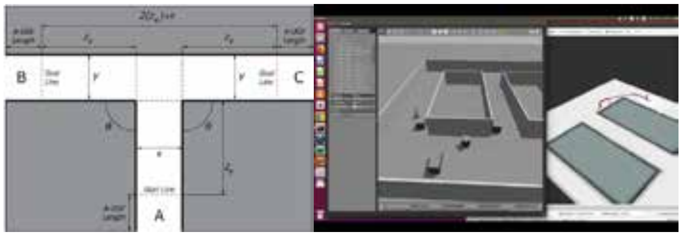
How does the assembly environment look like?

- Operation with humans and carts
- Time sensitive
- Extended operating times
- Moving goals

Benchmarking standards lack robustness metric

ASTM standard used to provide a reference for a benchmarking arena



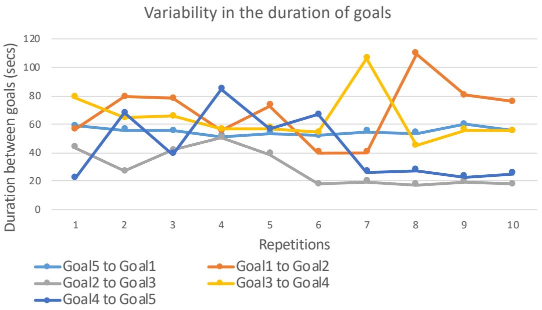


ASTM standard F3244-17 reference test area designed in Gazebo

Gill, J.S., Tomaszewski, M., Jia, Y., Pisu, P., Krovi, V., "Evaluation of Navigation in Mobile Robots for Long-Term Autonomy in Automotive Manufacturing Environments," SAE Technical Paper 2019-01-0505, 2019. https://doi.org/10.4271/2019-01-0505

Navigation Stack Benchmarking (Simulated Environment)

- Simulated model for YMR12 base unavailable
- Fetch robot high fidelity model was adapted for benchmarking the ROS Navigation stack
- Inconsistency in timed runs observed. Consistency important for assembly environment
- To validate, tests conducted on robots



Test area – Static obstacles; Static Environment

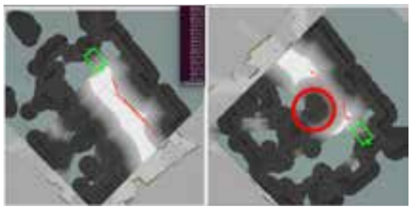
Across 10 runs

	Mean Duration	Std Dev
Goal5 to Goal1	55.0536	2.72574643
Goal1 to Goal2	68.7308	21.14284212
Goal2 to Goal3	29.2132	12.91495016
Goal3 to Goal4	63.8461	17.34981768
Goal4 to Goal5	43.8468	23.03002309

Gill, J.S., Tomaszewski, M., Jia, Y., Pisu, P., Krovi, V., "Evaluation of Navigation in Mobile Robots for Long-Term Autonomy in Automotive Manufacturing Environments," SAE Technical Paper 2019-01-0505, 2019. https://doi.org/10.4271/2019-01-0505

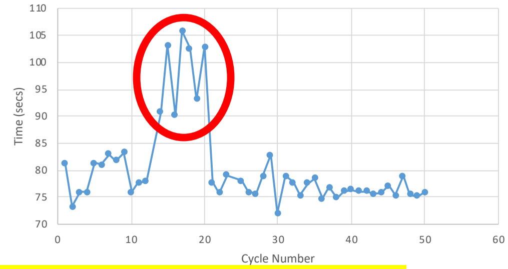
Experiments with YMR12 (Blackbox)

YMR cycles between Goals 1 to 2 (red arrows) for 50 cycles.



Local costmap of the robot generated by local planner: Left – without obstacle. Right - Static obstacle (a cardboard box) introduced in cycles 14-20

Time taken for a cycle of path planning in ARMLAB



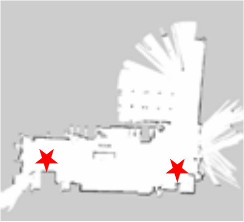
Mean for no obstacles(s)	76.83
Std dev (s)	1.30

Mean for obstacles (s)	98.36
Std dev (s)	6.69

Gill, J.S., Tomaszewski, M., Jia, Y., Pisu, P., Krovi, V., "Evaluation of Navigation in Mobile Robots for Long-Term Autonomy in Automotive Manufacturing Environments," SAE Technical Paper 2019-01-0505, 2019. https://doi.org/10.4271/2019-01-0505

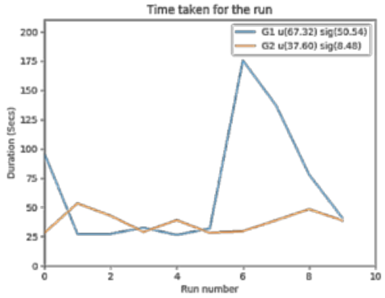
Moving to a Robot with Open Access (Ridgeback)

G1

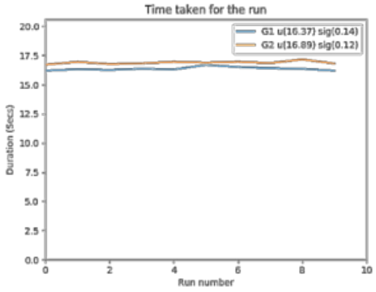


Occupancy grid map of CMI laboratory

G2



Fine tolerance runs– 2.5 cm. Optimization possible due to open access



Demo 2: Navigation Through Changing Environment

Online map updating not needed

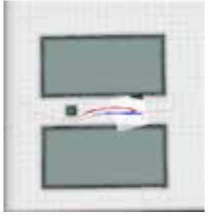
1. Robot using an **<u>obstacle-free map</u>** to navigate through an ***environment with obstacles***

Map updating needed

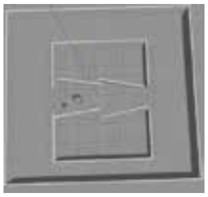
1. Robot using a **<u>map with obstacles</u>** to navigate through an environment ***without obstacles or with known obstacles but with changed layout***
2. Robot using a map to navigate through an environment ***with changes in structural elements***

Ridgeback dynamic obstacle avoidance (slow moving) using teb_local_planner

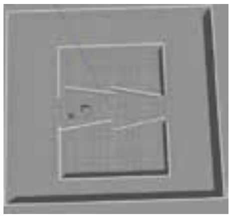
Robot map



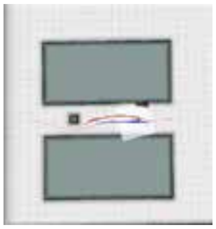
Environment



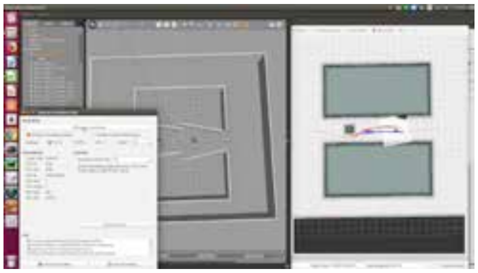
Benefit of Online Map Updating



Environment

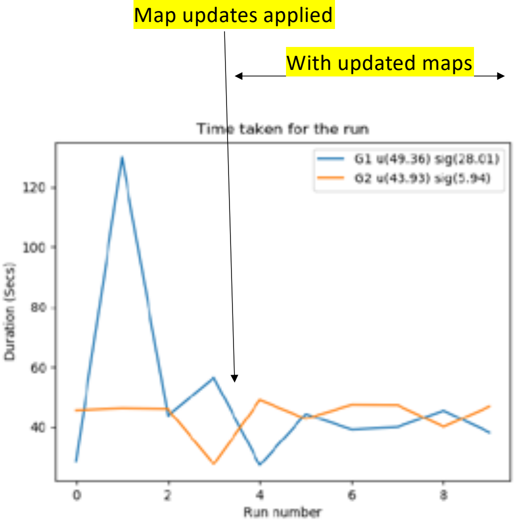


Robot map



Map updates applied

With updated maps

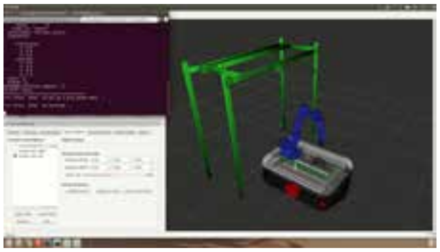


Task 3: Manipulation Planning and Control

- Objective
  - Generating manipulator trajectories to pick up and deliver a torsion bar in automotive assembly environment
- Challenges
  - Detecting and localizing the objects
  - Planning and controlling the manipulator motion in the presence of static obstacles

Task 3: Manipulation Planning and Control

1st Quarter



Simulation development using MoveIt! in ROS

2nd Quarter

Manipulation Motion Planning and control in simulation context

3rd Quarter

Manipulation planning and control in realistic context

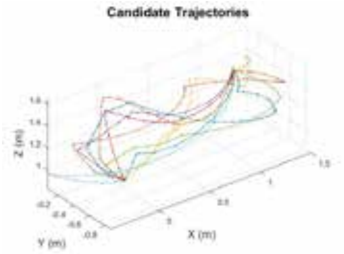
4th Quarter

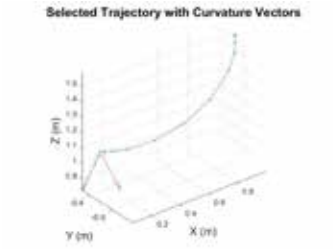
KPP Evaluations and validate outcome transitions to other robots

Task 3: Manipulation Planning and Control

New Manipulation Challenges in Manufacturing Process

- **Manipulation Requirements in Manufacturing Process**
  - Consistent time cost and consistent motion to accomplish manipulation tasks in human-robot collaboration
  - Consistent time cost is for line balancing and consistent motion is for collaboration safety and efficiency
- **Challenges**
  - Existing real-time manipulation motion planning algorithms are probabilistic approaches, which leads to inconsistency in time cost and motions
  - Different algorithms give different manipulation solutions
  - The same algorithm may also give different solutions in different runs





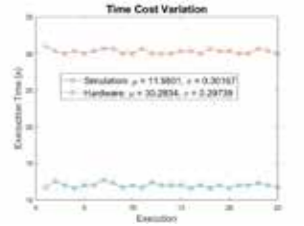
$$\min: C(\xi) = w_t \times (t_{post} - t_{start}) + w_p \times L_p + w_{Tj} \times D_{Tj} + w_{mi} \times \frac{1}{N}\sum_{i=1}^{N} I_i$$

$$s.t. \quad \min(I_i) > I_{threhold}$$

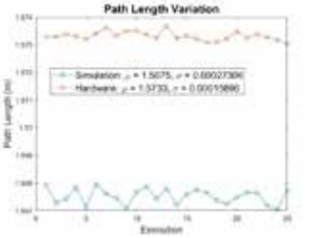
$$score = \exp(-C(\xi))$$

Task 3: Manipulation Planning and Control

KPP Evaluation



Time consistency

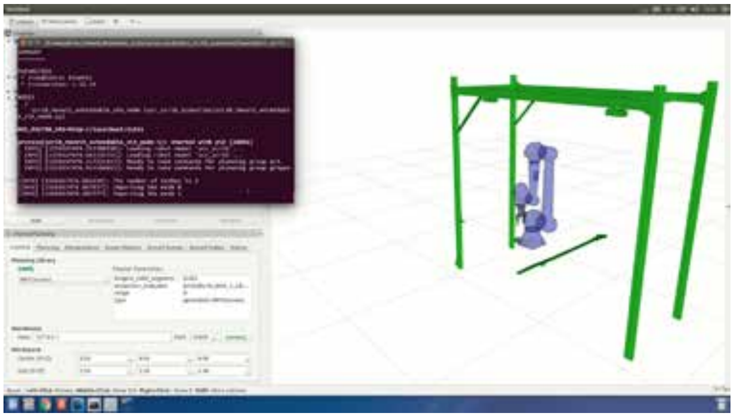


Motion consistency

- **KPP Evaluation Results**:
  - In hardware test, the robot can reach up 250 mm/s. For safety reasons, we slow down the robot for safety purpose.
  - The planning time to generate a new solution in real time is less than 0.06 second. The path planning update frequency can reach up to 15 Hz if necessary.
  - Accuracy to arrive at destination (x, y, z) is +/- 0.1 cm.
  - The torsion bar manipulation is evaluated by running for 25 trials. Zero failure was found in obstacle avoidance and handover process.
  - The time cost and motion in hardware evaluations are as consistent as simulations

Task 3: Manipulation Planning and Control

- Outcome Transition Test on HC10 Collaborative Robot
  - A new HC10 robot is tested in our developed motion planning and control framework for the same task
  - Results show that our outcome is not limited by robots and can be easily transited to other robotic applications



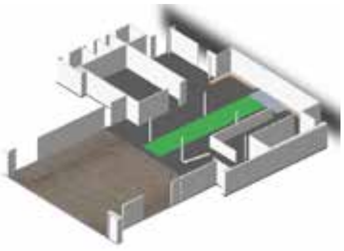

SCR1.0a

HC10 (SCR1.0b)

HC10 collaborative robot

Task 4 : Approach

From 2D Design → To 3D Detailed Model → To Real-Life Digital Environment



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Period 1 (months 1-6) [3D modeling in Siemens NX]
- Creating CAD model vehicle assembly center
- Model platform, vehicle body, and over head assembly structure
- Design various what-if-scenarios for simulation/testing

Period 2 (months 7 – 12) [Digital Twin Simulation]
- Create digital human model for testing what-if-scenarios
- Conduct human factor, collision, reachability and process time analysis in digital environment

Deliverables

- **DELIVERABLE 1: CAD model of the simulated environment (generated with NX Mach 3 product design software) as well as simulated workplace scenarios with digital model of the associate and the robot (generated with PS-Basic and PS-Jack software packages)**

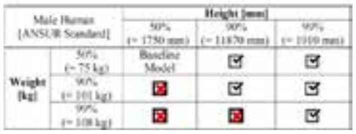
  - CAD model of the simulated environment is available as part of the Task 4 deliverable package, with files for
    - Overhead and Torsion Bar
    - Robot
    - Simulated environment
  - Guide on CAD Files.docx

Storyboard

- **DELIVERABLE 2: Detailed experimental protocol for each assembly scenario and Evaluation report of the plant simulation for identification of factors defining productivity, and cycle time.**

  - Human digital twin model is created based on the standardized biomechanical, anthropometric and ergonomics characteristics tables.
  - ANSUR database using varying male and female forms.

Table 1: Initial DoE table for male human model



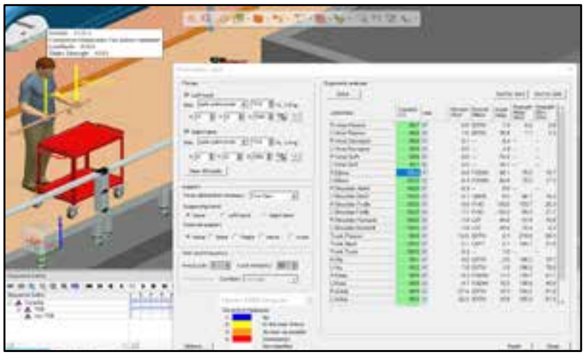
Male Human [ANSUR Standard]		Height [mm]		
		50% (= 1750 mm)	90% (= 1870 mm)	99% (= 1910 mm)
Weight [kg]	50% (= 75 kg)	Baseline Model	☑	☑
	90% (= 101 kg)	☒	☑	☑
	99% (= 108 kg)	☒	☒	☑

Table 2: Initial DoE table for female human model

Female Human [ANSUR Standard]		Height [mm]		
		50% (= 1630 mm)	90% (= 1740 mm)	99% (= 1780 mm)
Weight [kg]	50% (= 63 kg)	Baseline Model	☑	☑
	90% (= 79 kg)	☒	☑	☑
	99% (= 85 kg)	☒	☒	☑

Deliverables

- **DELIVERABLE 3: Ergonomic evaluation of human operation.**
  - Force analyzer tool for calculating forces and moments on human joints in static posture and then ergonomic standards for evaluation of human posture such as ability to carry load, or fatigue are introduced.
  - Effect of weight and height on these metrics for both male and female models.

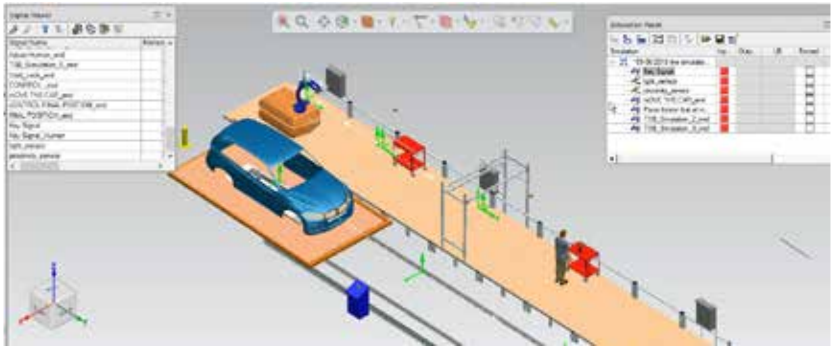


Ergonomic Standards

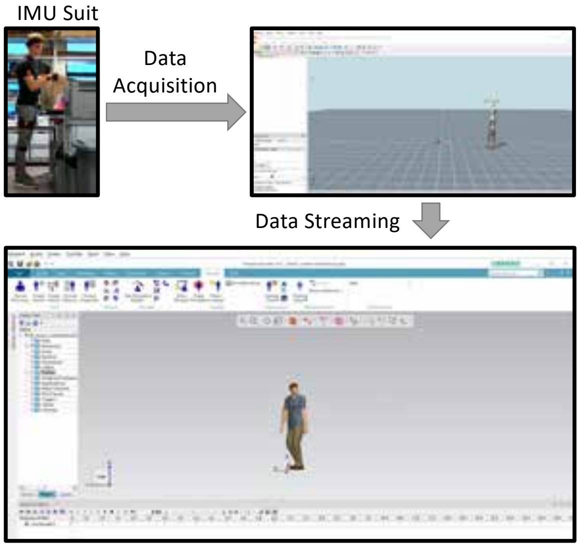
- National Institute for Occupational Safety and Health (NIOSH): Recommended Weight Limit (RWL) and Lift Index (LI).
- Ovako Working-posture Analyzing System (OWAS): Used for analyzing standard body postures (back, arms, legs, head), reported as work codes (1 = "no correction needed" to 4 = "immediate correction".
- Fatigue Analysis (Rohmert and Laurig): Time for a given job cycle to avoid worker fatigue. Considers only effect of muscle stress in the calculation of endurance.
- Lower Back Analysis (LBA): Calculates spinal forces acting on the human model's lower back, under any posture and loading condition.
- Cumulative Lower Back Load (CLB): Considers the impact of task demands that are performed over an entire work shift.

Deliverables

- **DELIVERABLE 4: Evaluation of the developed Smart Companion Robot for human ergonomic aspects and safe interaction using the human associate's digital twin in different assembly scenario.**
  - Comparison of ergonomic results in human-only and human-robot simulations
  - Improvements in OWAS, Fatigue and LBA analysis were discussed in details.



Demo 4: Data Driven Human Motion Simulation & Analysis



IMU Suit

Data Acquisition

Data Streaming

Siemens Process Simulate Human

Human Motion Capture

Data driven human in Siemens Process Simulate

Clemson University · International Center for Automotive Research
February 2019

ARM SMART COMPANION ROBOT PROJECT

Phase I : March 15, 2018 – March 15, 2019

Presented at ACC 2019 Workshop
Robot Assisted Manufacturing: Challenges and Opportunities
Tuesday July 9

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