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Enabling the Electric Future of Mobility: Robotic Automation for Electric Vehicle Battery Assembly

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ABSTRACT Consumer demand for Electric Vehicles (EVs) is increasing due to improving performance and affordability. However, EV manufacturers are struggling to meet this rise in demand. A key bottleneck is supply from a nascent EV battery supply chain that is new and developing. In this paper, we propose robotic work cell design for fast and reliable assembly of EV battery modules, at scale, to reduce this demand-supply gap.

INDEX TERMS Automation, digital simulation, digital twin, electric vehicles, EV batteries, industrial robots, lithium ion batteries, robots, robotic assembly.

I. INTRODUCTION

A. EV DEMAND IS UP

Even though electric vehicles(EVs) account for only a small percentage of all vehicle sales today, there has been a steady and sharp increase in consumer adoption. According to the 2018 IEA Global Electric Vehicle Outlook, new registrations of EVs increased from 111,320 in 2013 to 750,490 in 2017, a 575 percent increase [1]. A 2018 survey by AAA found that consumer interest in electric vehicles is increasing, with 20 percent or 50 million Americans likely to go electric for their next vehicle purchase, up from 15 percent in 2017 [2]. This increase in acceptance has been supported in part by incentives for the adoption of electric vehicles in several countries. These incentives coupled with the dramatic fall in battery prices (Fig. 1) and increase in driving range per charge, has resulted in increasing acceptance of EVs by consumers, as reflected in their rising demand (Fig. 2).

B. EV PRODUCTION IS UP

To capitalize on this rising demand for EVs, most major automotive firms have announced ambitious plans (Table. 1) to expand their current line up of EV models (Table. 2). For instance, in 2019, BMW announced that it is fast forwarding its EV plans by two years [3]. The Volkswagen group, in its 2019 annual press conference, announced plans to launch 70 new electric cars by the end of 2028, up from a previous plan of 50 [4]. In a blog post on LinkedIn in Sept. 2018, GM's CEO Mary Barra, said that the Chevy Bolt EV may be more popular with buyers than the automaker expected. The automaker announced plans to increase production of the Bolt by 20%. Further it transferred the production of batteries from South Korea to near Bolt's final assembly plant in Orion township in Michigan, USA.

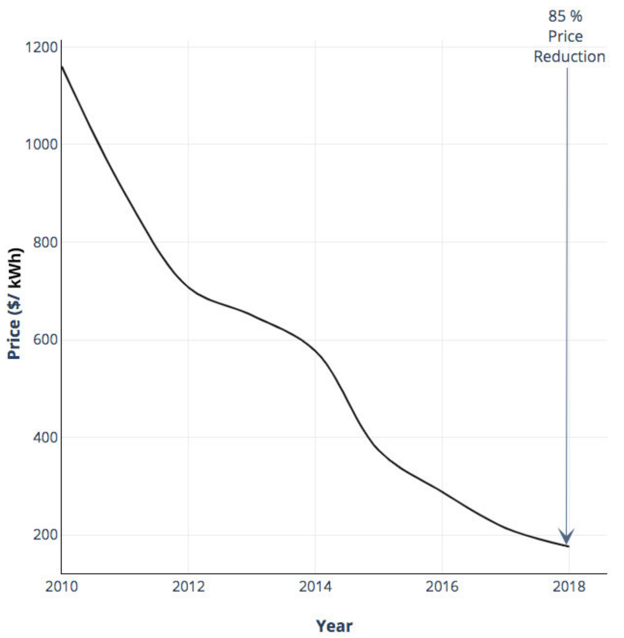

FIGURE 1. Average EV battery pack price (Source: Bloomberg, 2018).

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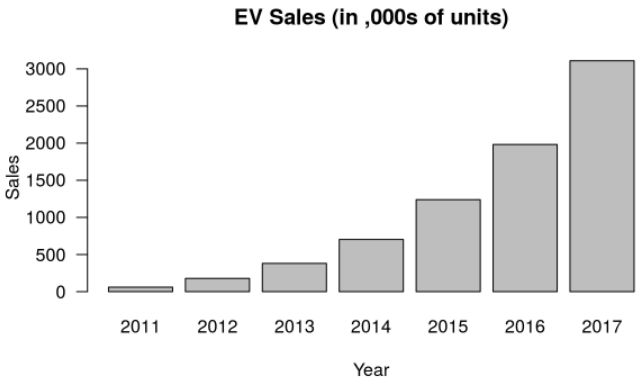

FIGURE 2. **Global electric vehicle sales by year (Source: InsideEVs.com, Hybridcars.com).**

C. EV FIRMS ARE STRUGGLING TO MEET RISING DEMAND

As automotive original equiment manufacturers (OEMs) try to ramp up production to meet the rising demand for EVs, they seem to be facing challenges. For instance, TESLA motor company has frequently been in the news for not meeting its production targets [5], [11]. In May 2016, CEO Elon Musk, estimated that the company would make 100,000 to 200,000 Model 3s during the second half of 2017. Tesla made 2,685 Model 3 vehicles in 2017 [11]. Other automotive OEMs are also not able to produce enough EVs to meet demand [6]. This is surprising for an industry that has perfected the science of manufacturing at scale, and is plagued with production over-capacity.

D. EV BATTERY PRODUCTION HAS EMERGED AS THE BOTTLENECK

A closer look at the challenges automotive OEMs are facing in manufacturing EVs reveals that a key bottleneck is their inability to assemble enough EV batteries. For instance, Tesla, arguably a pioneer is mainstreaming EVs, has pointed to battery assembly as one of the main bottlenecks in meeting its production targets [7].

In its 2018 Q1 Letter to Shareholders [10], Tesla, highlighted the battery module line as one of the slowest parts of its supply chain.

> As with all manufacturing, Model 3 production can only go as fast as the slowest part of the entire supply chain and production process. For months, the battery module line was our main production bottleneck. After deploying multiple semi-automated lines and improving our original lines, we have largely overcome this bottleneck.

In addition to TESLA, other players in the automotive industry are also facing challenges in meeting battery demand [8]. The slow pace of battery assembly is due to the salience of manual work in the current battery assembly process. In an interview with Bloomberg [13], CEO Elon Musk has described the TESLA factory as a mix of automated and human work.

> There are parts of it that are completely automated, no person there at all. And then there are parts of it which are completely manual, no machines there at all. Then there are parts of it that are partly automated and partly manual.

Attempts at automation have thrown up challenges. In its 2017 third quarter letter to shareholders [9], TESLA identified its battery module assembly line as a bottleneck, citing challenges in automating it as an underlying cause.

> "To date, our primary production constraint has been in the battery module assembly line at Gigafactory 1, where cells are packaged into modules. Four modules are packaged into an aluminum case to form a Model 3 battery pack. The combined complexity of module design and its automated manufacturing process has taken this line longer to ramp than expected. The biggest challenge is that the first two zones of a four zone process, key elements of which were done by manufacturing systems suppliers, had to be taken over and significantly redesigned by Tesla. We have redirected our best engineering talent to fine-tune the automated processes and related robotic programming, and we are confident that throughput will increase substantially in upcoming weeks and ultimately be capable of production rates significantly greater than the original specification."

While the reliance on manual work has supported current production levels, if EVs have to become a viable alternative to IC engine vehicles, automating the EV battery assembly process is essential. Currently, it is projected that by 2020, the global battery production capacity will stand at 268 gWh. According to some estimates, supporting the sales of 18 m. EVs will need over 800 gWh battery production capacity. Enabling such large scale production will require the EV battery industry to develop highly automated assembly processes that can produce quality EV batteries reliably at a high throughput rate.

However, currently, each OEM seems to have its own unique battery pack design and battery assembly process that remain heavily guarded secrets. For instance, in media interviews TESLA has admitted to over-automating its factory and underrating the role of human work [11]. This statement reveals that TESLA may have gathered insights into what necessitates the reliance on human work and whether and how automation can further improve the battery assembly process. Such 'learning by trial' by individual firms in isolation may keep these hard earned insights within the walls of an organization.

As we learnt from a seminal history of the automotive industry in "The Machine That Changed The World" [12], for the EV battery supply chain to evolve and mature, standardized components and automated production processes

TABLE 1. Electric vehicle production plan announcements by major automotive OEMs.

Company	Announcement Date	EV Models Target	EV Volume Target	Current Sales Volume
Toyota	Apr 2018	2020: 10 EVs	2030: > 1 M. EVs	10.2 M.
	Jun 2019		2025: 5.5 M. EVs	10.2 M.
Volkswagen	Nov 2018	2025: 50 EVs	2025: 2-3 M. electric cars/year	10.1 M.
	Mar 2019	2030: 70 EVs	2030: 15-22 M. electric cars	10.1 M.
Hyundai / Kia	Dec 2017	2025: 38 'green car' models		7.9 M.
	Dec 2018		2030: 700,000 EVs/Year	7.9 M.
GM	Oct 2017	2023: 20 EV models		7.8 M.
Ford	Jan 2018	2025: 40 electrified vehicles		6.4 M.
Nissan	Mar 2018		2022: 1 M. electrified vehicles/ Year	5.6 M.
Honda	Sep 2017	2019: 1 EV model		5 M.
	Feb 2016	2020: 1 EV model	2030: EVs 15% of sales by volume	5 M.
Fiat Chrysler	Jun 2018	2022: 30 EV models		4.7 M.
Groupe PSA	Sep 2018	2019: 15 electrified models		4.7 M.

TABLE 2. Battery supply chain of some electric vehicle models.

Company Model	Range (miles)	Battery Size(kWh)	Battery Cell Manufacturer	Battery Pack Manufacturer	Assembly Location
Tesla Model S	295-335	75 or 100	Panasonic/Tesla US	Tesla US	U.S
Tesla Model X	295	75 or 100	Panasonic/Tesla US	Tesla US	U.S
Tesla Model 3	220-310	50-74	Panasonic/Tesla US	Tesla US	U.S
Chevrolet Bolt EV	238	60	LG Chem US	LG Chem US	U.S
Nissan Leaf	151	30	Automotive Energy Supply Corp. US	Nissan US	U.S
Fiat 500e	84	24	SB LiMotive US	Fiat US	Mexico
VW e-Golf	126	35.8	Samsung SDI South Korea	VW Germany	Germany
Ford Focus Electric	118	33.5	LG Chem US	Ford US	U.S
BMW i3	114	22-33	Samsung SDI US	BMW US	Germany
Kia Soul EV	111	27	SK Innovation US	Kia US	South Korea

need to be developed. This paper is an attempt to make progress in this direction by proposing robotic automation solutions for fast and reliable EV battery module assembly at scale. As a fist step we do an extensive literature review to establish what is known about automating EV battery assembly.

II. LITERATURE REVIEW

We conducted an extensive review of extant research on EV battery assembly. The search for articles was conducted by the authors in three digital libraries: IEEE Xplore, Science Direct and Web of Science. A tabulation of the search terms and article counts is presented in Table 3.

The search yielded a total of 135 articles. 10 articles were duplicates which were removed from the result set. Articles that explored fundamental technology areas unrelated to batteries were also removed. We also excluded 40 articles that were related to battery technologies in the context of non-EV fields such as space exploration and wind mills. After excluding such papers, 72 papers remained which were related to electric vehicles batteries.

An analysis of these 72 papers revealed that these studies focused on different levels of an EV battery system - individual cell level, battery module level, battery pack level, EV level, grid level and system level. In addition, some of the papers studied EV battery pack components such as the battery management system and the thermal management system. A list of the key systems studied with article counts is summarized in Table 4.

Studies at the individual cell level are primarily focused on cell chemistry [14]–[18], cell charge estimation [19], and cell performance modeling [20]. Studies at the battery module

TABLE 3. Article count of literature review on electric vehicle batteries.

Database	Search Terms	Article Count
IEEE Xplore	Battery AND EV AND Pack AND Assembly	9
IEEE Xplore	Electric Vehicle AND Battery AND Pack AND Robotics	14
IEEE Xplore	Electric Vehicle AND Battery AND Pack AND Robot* AND Assembly	1
IEEE Xplore	Electric Vehicle AND Battery AND Pack AND Automation AND Assembly	2
IEEE Xplore	Electric Vehicle AND Battery AND Pack AND Assembly	23
IEEE Xplore	Electric Vehicle AND Battery AND Module AND Assembly	27
Web Of Science	Electric Vehicle AND Battery AND Module AND Assembly	0
Web Of Science	Electric Vehicle AND Battery AND Pack AND Robot* AND Assembly	0
Web Of Science	Electric Vehicle AND Battery AND Pack AND Automation AND Assembly	1
Web Of Science	Electric Vehicle AND Battery AND Pack AND Robotics	7
Web Of Science	Battery AND EV AND Pack AND Assembly	8
Web Of Science	Electric Vehicle AND Battery AND Module AND Assembly	12
Web Of Science	Electric Vehicle AND Battery AND Pack AND Automation	13
Science Direct	Title, abstract, keywords: EV AND Battery AND Module AND Assembly	1
Science Direct	Title, abstract, keywords: EV AND Battery AND Pack AND Assembly	2
Science Direct	Title, abstract, keywords: Electric Vehicle AND Battery AND Module AND Assembly	3
Science Direct	Title, abstract, keywords: Electric Vehicle AND Battery AND Pack AND Assembly	12

TABLE 4. Units of study in electric vehicle battery literature with article counts.

Unit of Study	Article Count
Battery Cell	7
Battery Module	3
Battery Pack	43
Battery Management System	6
Electric Vehicle	9
EV Charging Station	2
EV Grid	2
Total	72

level focus on module assembly [21], simulating module function [21], and simulation of the thermal condition of the module [22]. Studies at the battery pack level are focused on battery pack design [23]–[26], battery pack assembly [27], battery pack charge estimation [28]–[30], battery pack charge equalization, [31] battery pack charge simulation, [32] battery pack thermal management [33]–[35], [37]–[39], and battery pack thermal runaway prevention [36], [40]. Studies of battery management systems (BMS) focus on BMS design [41], [42]. Other studies on BMS explore the use of the BMS for cell balancing [43]–[45], cell equalization [46], and charging effectiveness [31]. Studies at the EV level focus on issues associated with integrating a battery pack with an EV [37], [72]. Studies at the grid level are focused on grid design [47], and battery charging strategies [48]–[50]. At a larger system level, research is focused on the design of charging stations [51], design and simulation of battery swapping mechanisms [52], EV battery reuse [53]–[57], and EV ecosystem considerations [52].

When considering battery assembly, surprisingly, there is a paucity of research in extant literature. Some studies have explored specific manufacturing technologies such as those used in joining automotive Li-ion batteries [58]. Others have developed mathematical models for designing an optimal assembly system with complex configurations by jointly considering product design hierarchy, line balancing, and equipment selection [27].

In sum, our literature review on EV battery assembly suggests that while there is extensive research on cell chemistries, battery management systems, estimating state of charge in batteries, battery charge balancing and battery charging technologies, there is limited coverage of battery module and pack assembly. As battery assembly emerges as a key bottleneck in meeting the rising demand for EVs, there is a clear need to study it with the goal of evolving a more efficient and effective assembly process. Specifically, there is a need to transition from the prevalence of manual to more automated processes. In this paper we make an attempt in this direction by designing and simulating robotic work cells for automating battery module assembly. We start with an overview of the structure of an EV battery in Section III, and the battery assembly process in Section IV.

III. THE EV BATTERY PACK

EV batteries vary on the dimensions of cell chemistry and cell format. When considering cell chemistry, Lithium-ion (Li-ion) batteries outperform other available cell chemistries in providing the maximum energy density(volumetric energy density) at the lowest weight (gravimetric energy density) (Fig. 3). Packing maximum energy in the least volume and weight helps increase the driving range between charges, reducing user anxiety. For this reason, Li-ion chemistry has emerged as the dominant cell chemistry in EV batteries. Additionally, Li-ion batteries have a long cycle life and low environmental impact which make them attractive for automobile applications.

Within the Li-ion cell chemistry, there are two primary formats that are in use in EVs today - cylindrical and

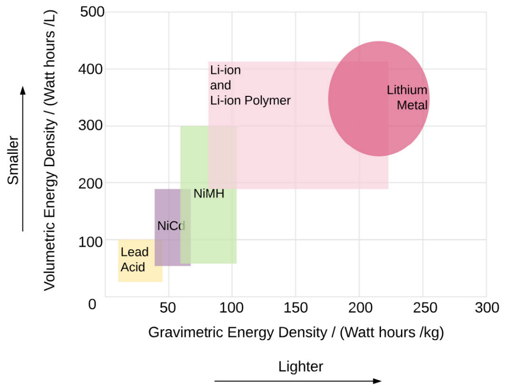

FIGURE 3. Gravimetric and volumetric energy density of cell chemistries.

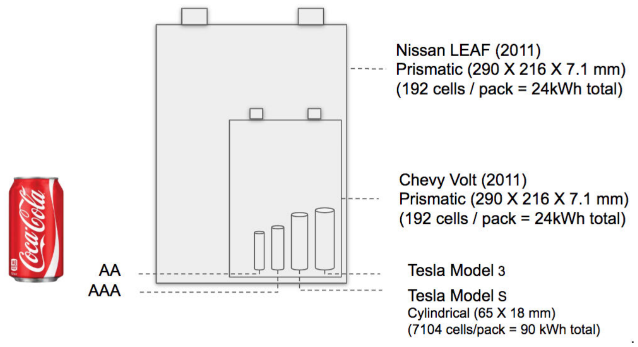

FIGURE 4. Battery formats (to scale).

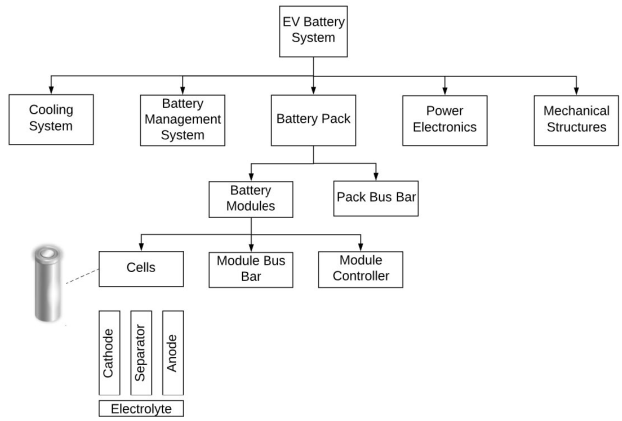

FIGURE 5. Electric vehicle battery system structure.

prismatic (Fig. 4). These two formats are almost evenly split in their share of use in EVs. Table 5 summarizes the battery chemistries and formats for some of the major EVs.

Irrespective of the battery chemistry and format, all EV batteries are made by assembling individual battery cells into progressively larger units. Individual cells are assembled into battery modules. Battery modules in turn are assembled into a battery pack. In addition to the cells, an EV battery contains other components such as battery module housing, battery pack housing, battery pack management system, battery module management system, thermal management system, power electronics, wiring and tubing, fasteners and joining components. Fig. 5 illustrates this hierarchy in a block diagram of a typical EV battery system.

IV. BATTERY PACK ASSEMBLY PROCESS

The input to the EV battery pack assembly process are individual cells and the components, as illustrated in Fig. 5. The output is the battery system ready to be integrated into an EV. While the details of the assembly process vary depending on the chosen cell format and the manufacturing steps adopted, broadly, it consists of the following stages: (I) Aggregating individual cells into battery modules, (II) Aggregating battery modules into a battery pack (III) Adding additional components and peripherals to the battery pack to complete the EV battery system, and, (IV) Testing and certifying the battery system as ready for integration into a vehicle.

While, these broad steps for battery assembly remain similar across OEMs, the details may vary across different battery formats as well as between OEMs, for the same battery format. Thus, in order to design an automation solution for the battery assembly process, we need to consider a specific battery model. For this paper, we have chosen the Tesla Model S battery module as our reference case.

We chose Tesla because it arguably is a pioneer in EV vehicles with significant experience in assembling battery systems for EVs. Additional reasons were the availability of TESLA patents in the public domain [65], which was very helpful in arriving at a good understanding of the battery module structure as well as its assembly process. This understanding was critical in arriving at a realistic automation system design. In addition to patents, we gathered information from publicly available information such as videos of battery tear downs, online blogs, trade magazines, company fillings, company press releases and letters to shareholders.

To design the automation system, we collaborated with robotic engineers and automation experts from one of the largest robotic automation systems integrator in the world. This firm has been automating automotive and other manufacturing facilities worldwide for around 40 years. The experts we consulted have experience between 10-30 years in design and implementation of robotics and automation solutions. This helped ensure that the automation solutions we have proposed are ready for real world implementation.

In what follows, we first provide details of the Tesla Model S battery pack in section V and the battery module in section VI. Based on our understanding of the battery module structure, we propose an assembly process for the battery module in section VII. We use this understanding of the assembly process to evaluate it for robotic automation in section VIII. In section IX we present our approach to designing the robotic work cells, and in sections X - XIV, we provide the detailed designs of each of the robotic work cells. Finally, in section XV we describe our simulation approach and present the results of our simulation of the robotic work cells.

TABLE 5. Battery Chemistry, Format and vendors for major electric vehicle models.

Company	Country	Vehicle Model	Battery Chemistry	Battery Format	Vendor
Audi	Germany	e-Tron	Li-ion	Pouch	LG Chem
BMW	Germany	X6, Mini E	Ni-MH	Prismatic	Panasonic
Chrysler	USA	200C EV	Li-ion	Prismatic	A123 Systems
GM	USA	Chevy Bolt	Li-ion	Pouch	LG Chem
Ford	USA	Focus Electric	Li-ion	Pouch	LG Chem
Honda	Japan	Civic, Insight	Ni-MH	Prismatic	CATL
Mitsubishi	Japan	i-MIEV	Li-ion	Prismatic	GS Yuasa
Nissan	Japan	LEAF	Li-ion	Prismatic	NEC
Tesla	USA	Model S	Li-ion	Cylindrical	Panasonic
Tesla	USA	Model X	Li-ion	Cylindrical	Panasonic

While our work cell designs and simulations are based on the Tesla Model S battery module, they are generic enough to be applicable for assembling cylindrical cells into EV battery modules with alternative designs.

V. THE TESLA BATTERY PACK

The Tesla Model S battery pack consists of 7104 individual 18650 (65 mm × 18 mm) Lithium Ion cells connected in a series and parallel configuration to achieve the desired voltage and capacity. Instead of being a single assembly of 7104 cells, the pack is assembled from 16 identical battery modules. Each Tesla model S battery module consists of 444 individual Li-Ion cells stacked in a 74p6s configuration. The 74p implies that 74 cells are connected in parallel to each other to form a group. The 6s implies that six such '74p groups' are connected in series with each other.

When connected in parallel, the positive terminal of the first cell is connected to the positive terminal of the next cell, and the negative terminal of the first cell is connected to the negative terminal of the next cell. In a parallel connection, the voltage of the configuration remains the same as the cell. Since each 18650 cell has a nominal voltage of 3.8 V, a 74p grouping also yields 3.8 Volts. When connected in series, the positive terminal of a cell is connected to the negative terminal of the next cell, and the voltage of individual cells gets added up. Hence a 6s configuration yields 22.8 Volts (6 × 3.8).

Capacity of cells connected in parallel gets added up while those connected in series do not. The Tesla Model S battery pack consists of 16 battery modules connected in parallel. Since the EPA rated capacity of the pack is 84 kWh, each module has a capacity of 5.3 kWh. This also implies that each of the six, '74p', group of cells in the module, also have a capacity of 5.3 kWh. Thus a 74p6s configuration battery module yields 5.3 kWh capacity and 22.5 Volts. This is illustrated in a schematic of a 74p6s module in Fig. 6.

In a TESLA model S battery pack 16 such modules are assembled together inside a battery tray. Each of these 16 modules is connected in parallel to the central bus bar in the battery pack through the M8 bolt terminals on the

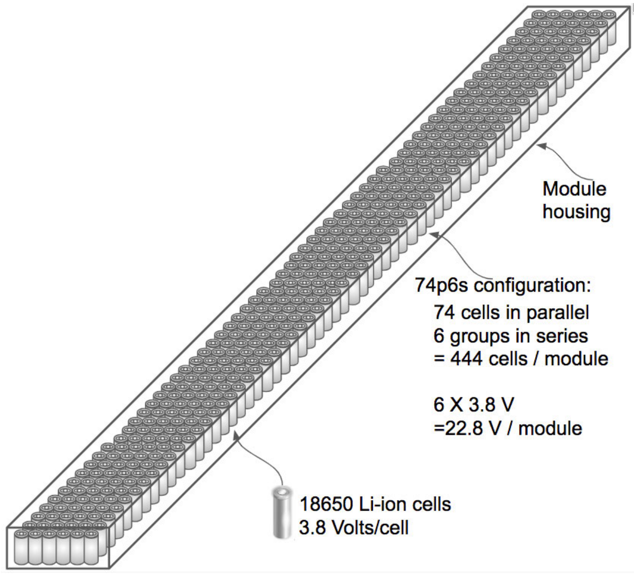

FIGURE 6. Tesla Model S, 74p6s battery module schematic.

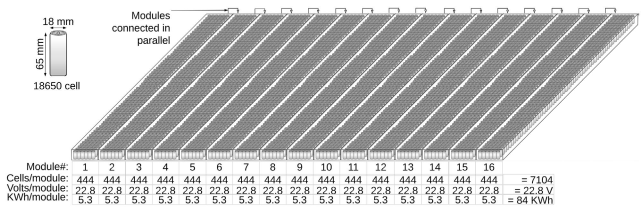

FIGURE 7. Tesla Model S, 84kWh battery pack schematic.

battery module. The battery pack central bus bar collects current from all the modules and takes it to a contactor which feeds it to the electric drive. The battery pack generates 22.8 Volts and 84 kWh (16 × 5.3 kWh), in a Model S battery pack as illustrated in Fig. 7.

Since this paper is focused on battery module assembly, we next look, in more detail, at the structure of the Tesla Model S battery module.

VI. THE TESLA BATTERY MODULE

In addition to the assembled cells, the battery module contains components including the cooling system, module

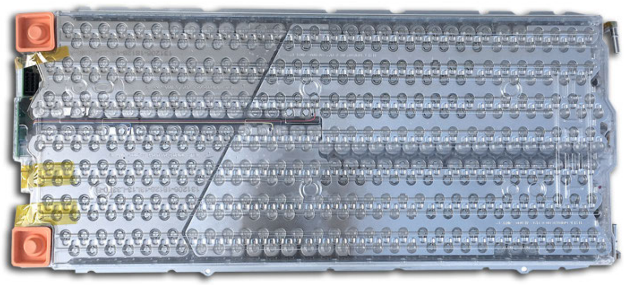

FIGURE 8. Tesla Model S battery module.

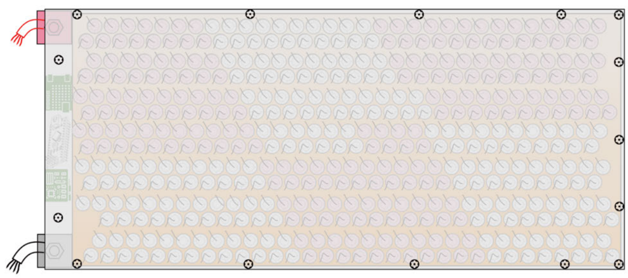

FIGURE 9. Tesla Model S battery module (top view schematic).

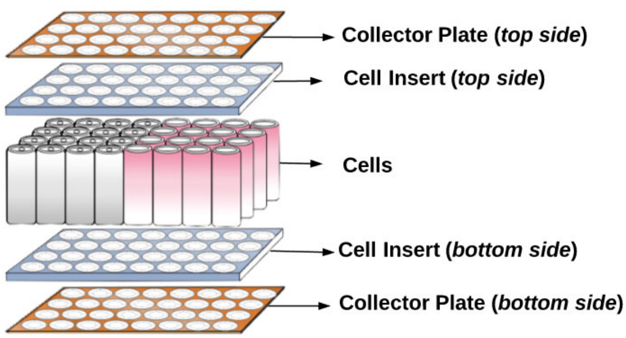

FIGURE 10. Battery module key components.

management system, wiring and other electronic components. All these components are placed inside a battery module housing structure which is a box shaped enclosure made of Aluminum. This module housing consists of a lower member and a complementary top cover. A sealing gasket is placed between the mating surfaces of the lower and upper housing members to make this structure impregnable to water, water vapor and other liquids and gases. Fig. 8 provides a top view image of the module while Fig. 9 provides a schematic of the top view.

An exploded view of the cell assembly inside the battery module, clearly reveals that inside the battery module, the 18650 Li-Ion cells are held vertically, sandwiched between a pair of complementary cell inserts (Fig. 10). The cell inserts are made of flame retardant poly-carbonate plastic and contain a multitude of complementary cylindrical retaining holes called cell-wells [61] (Fig. 11).

The cells are held vertically by inserting their ends in the cell-wells in the top and bottom cell inserts. The cell-wells are shallow relative to the height of the cells [61] and may not provide enough retaining force to hold them

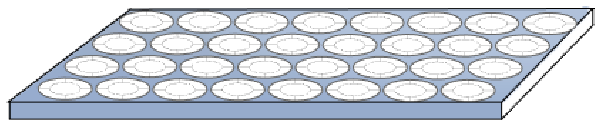

FIGURE 11. Battery module cell insert.

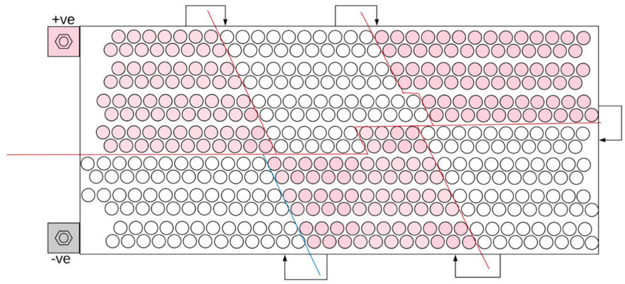

FIGURE 12. Tesla Model S, 74p6s battery module cell stacking arrangement (Note: red cells indicate +ve side up).

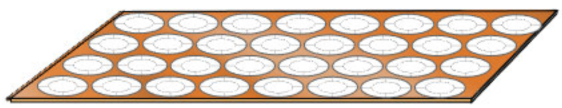

FIGURE 13. Battery module collector plate.

structurally, especially when subject to strong vibrations as may be common in a running vehicle. In order to increase the structural integrity of the module, an adhesive such as Loctite is dispensed in the cell-wells, to penetrate the spaces remaining between the cell and the cell inserts. This adhesive securely bonds each cell to the cell-insert. Sufficient adhesive is used such that it completely covers the end surface of the cells, thereby providing a structurally sound support for the cells [61].

The cells are arranged with the positive or negative terminals facing up in a specific pattern, to achieve the desired voltage and capacity for the battery module. The actual pattern in which the cells are arranged physically inside a battery module housing is illustrated in a top view schematic of the module (Fig. 12). The red cells indicate cells whose positive terminals are facing up and the white cells indicate cells whose negative terminals are facing up.

The cell-wells in the cell-inserts are through-holes, to keep the cell terminals exposed for making connections. On top of the cell inserts on each side of the module, current collector plates are placed (Fig. 10). These current collector plates are made of copper and contain holes that align with the holes in the cell inserts which ensures that the cell terminals remain exposed for making connections (Fig. 13). The cell terminals are connected to the current collector plate using aluminum fuse wires (Fig. 14). These individual cell level connections ensure that in the case of a short circuit event, the failure is isolated and the risk of sustained arcing and a thermal run is minimized [59].

Current collected, from the individual cells, in the collector plate is made available through two M8 bolt terminals at

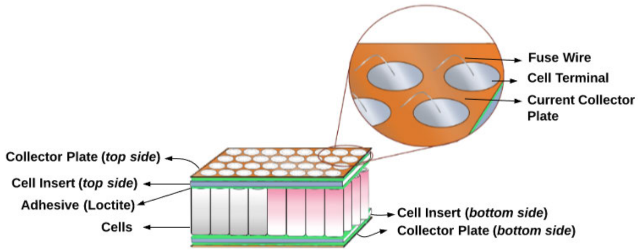

FIGURE 14. Battery module fuse wires.

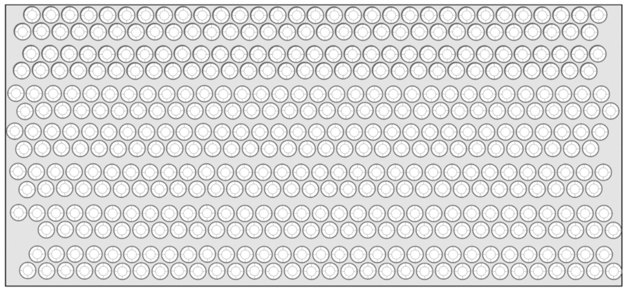

FIGURE 15. Battery module cell insert (top view).

the end of the module. These M8 bolts serve as the positive (red colored in Fig. 9) and negative terminals of the battery module.

VII. TESLA BATTERY MODULE ASSEMBLY PROCESS

In this section, we layout a high level specification of the battery module assembly process. This process is based on an extensive research of publicly available information sources such as academic and industry publications, patents in the public domain, battery tear down videos, company news releases and letters to shareholders.

The battery module assembly process starts with inspecting the individual cells for quality and uniformity. It is critical to ensure that the cells are of uniform size, are free of defects and have uniform voltage. Uniformity across the cells leads to higher performance and longer life for the module. This can be achieved through a combination of various automated tests before the cells are fed in for assembly. Cells that do not meet the desired parameters are rejected.

Cells that pass the quality checks are used for assembling the battery module. Assembly starts by inserting individual cells into the cell-wells in the bottom cell-insert. The cells must be spaced evenly to enable even cooling of the batteries and prevent accidental touching of the cells. Further, even spacing of the cells helps in improving the performance of the battery module. The cells are inserted such that the positive or negative terminals of a cell faces up to achieve the desired pattern of polarities. It is critical to ensure that the cells correct polarity is facing up. An error at this stage might result in uneven voltage in the module.

Once all the cells hae been inserted, the top cell-insert is positioned over the cells such that the top end of each cell gets inserted within the corresponding cell-wells of the top cell-insert. At this stage, a temporary latching mechanism may be used to hold the cells together and provide additional structural stability for subsequent operations.

After the cells have been sandwiched between the top and bottom cell-inserts, an adhesive such as Loctite is dispensed in the space between the cell ends and the cell- insert. The adhesive is expected to penetrate the interstices and spaces between the cell and the cell insert. This adhesive securely bonds each cell to the cell-insert. Sufficient adhesive should be used such that it completely covers the end surface of the cells, thereby providing a structurally sound support for the cells. After application of the adhesive, a current collector plate is placed on the top cell-insert such that its holes align with the holes in the cell-insert. After placement, the collector plate is gently pressed to ensure that proper bonding of the collector plate with the top cell-insert takes place.

At this stage, the battery module is flipped over and the process of attaching the cell-insert, dispensing adhesive in the cell-wells and bonding a current collector plate is repeated for the bottom side of the battery module. During this process, it is critical to ensure that the adhesive completely fills up the interstices. Additionally, the adhesive should be dispensed at a specified and uniform rate with uniform adhesive bead size, to prevent uneven application resulting in variability in weight and other characteristics of the battery.

After adhesive application, the module passes through a curing station to ensure that the adhesive cures properly. After the adhesive has cured and hardened, the cured module structure is taken to a wire bonding machine where aluminum fuse wires are used to bond the cell terminals to the current collector plates. This terminal bonding process is completed on both sides of the battery module. Once the fuse wires are bonded to the cells, this wire bonded stack of cells is placed inside the bottom member of the battery module housing structure.

The next step consists of manually assembling the remaining electrical, electronic and thermal components inside the battery module housing. At this stage, a variety of quality checks are also completed for the battery module. A sealing gasket is then placed between the complementary and mating surfaces of the lower and upper housing members. A final inspection check of the module is completed before closing out the module. A cover is then placed on top of the module and is bolted to seal the module. This completes the assembly of the battery module which is now ready to be used in a battery pack.

A schematic rendering of the battery module top view through the various stages of the assembly process is presented in Figs. 15-24.

VIII. EVALUATION OF BATTERY MODULE ASSEMBLY PROCESS FOR AUTOMATION

For evaluating the battery module assembly process for automation, we consulted with industrial robotics automation experts in the areas of material handling, adhesive

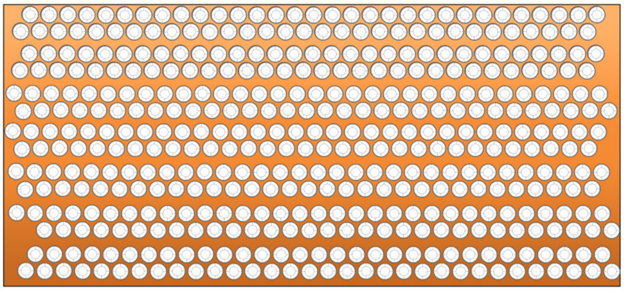

FIGURE 16. Current collector plate (top view).

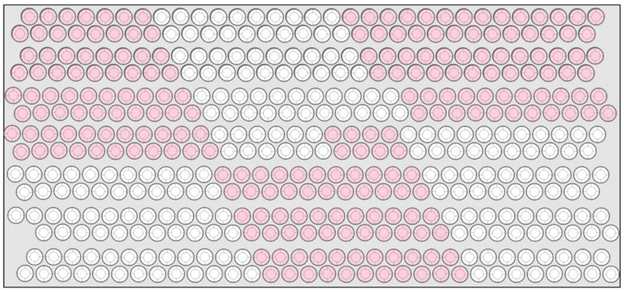

FIGURE 17. Li-Ion cells placed inside cell insert (top view).

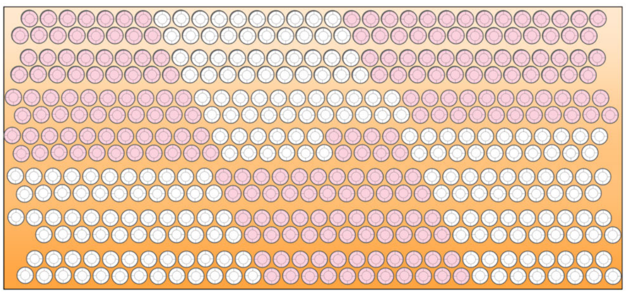

FIGURE 18. Collector plate adhesive bonded to cells and cell insert (top view).

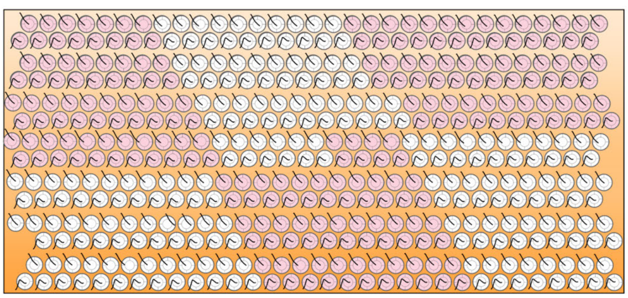

FIGURE 19. Cell terminals wire bonded to collector plate (top view).

dispensing, screw running and machine vision. These experts have between 10-30 years experience designing, validating, implementing and supporting robotic automation solutions in the automotive and other industries. The panel of experts was presented with a description of the manufacturing process, product requirements and process constraints. For each step, we determined how a human operator and a robot would execute the steps. Additionally a judgment was made whether the

FIGURE 20. Battery module housing (top view).

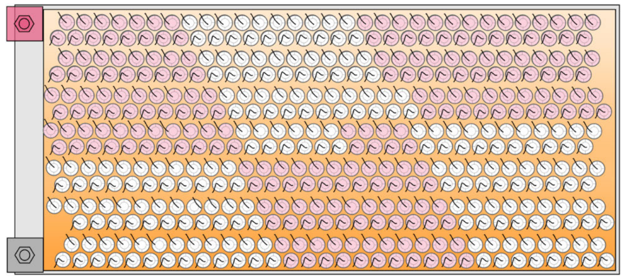

FIGURE 21. Wire bonded cell stack inside module housing (top view).

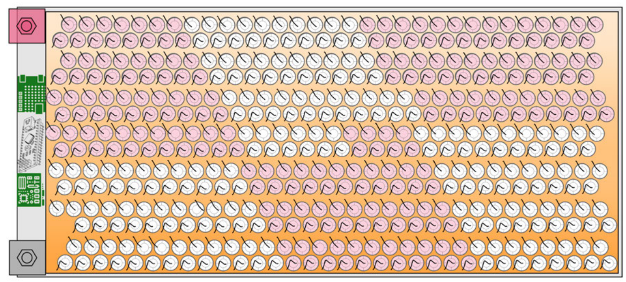

FIGURE 22. Electrical, thermal and other components of battery module inside housing (top view).

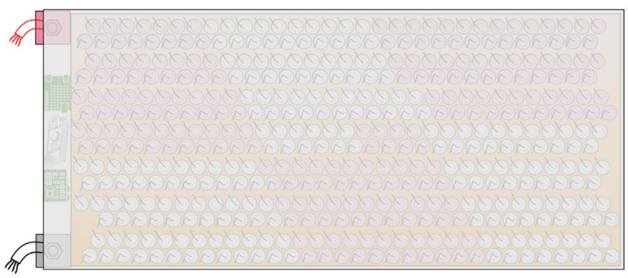

FIGURE 23. Battery module with top cover (top view).

steps could be executed by a robot while meeting the process constraints and product requirements. For each step, we also ascertained whether a robot or human would be superior in executing it. A summary of the process plan, the process requirements and a description of the task as executed by a human operator and a robot is presented in Tables. 6 and 7.

A review of these tables from an automation perspective reveals that all steps in battery module assembly are good candidates for robotic automation except for the steps involving

TABLE 6. Steps for electric vehicle battery module assembly using cylindrical cells.

No.	Work Center	Manufacturing Step	Requirement	Manual	Automated
1	Cell Sorting	Test for cell size	Cells should be of uniform size	Visual Inspection	Machine Vision
	& Inspection	Test for cell voltage	Cells should have uniform voltage	Check manually using voltmeter	Automated in-line voltage check
			Cells should have voltage between 3.5 and 4.2 volts	Check manually using voltmeter	Automated in-line voltage check
		Test for surface defects	Cells should not have any surface defects	Visual inspection	Machine vision
2	Cell Stacking	Pick cell from in-feed conveyor	A single good cell should be picked	Pick cell with hand while visually determining if cell is defective	Robotic gripper picks cell after machine vision check for defects
		Determine destination cell-hole in cell-holding template	Optimize for time taken and ergonomics	Human operator determines empty cell hole quickest and easiest to reach	Robot determines cell hole quickest to reach. Ergonomics not a concern for Robot.
		Move cell to destination cell-hole	Speed	Human operator moves cell quickly to cell hole	Robot moves cell quickly to cell hole
		Insert cell in destination cell-hole	Correct Orientation	Human picks cell with correct polarity facing up	Robot picks cell with correct polarity facing up
			Prevent interference	Human operator ensures that cell does not clash into already stacked cells	Robot plans path to avoid interference with already stacked cells
			Precision	Human operator inserts cell precisely in cell-hole	Robot precision should be high enough to ensure precise insertion into cell-hole
		Quality check	Completeness	Human operator checks visually to ensure all cell-holes in cell-holding template have cells in them	Machine vision check to ensure all cell-holes in cell-holding template have cells in them
			Correct pattern	Human operator checks visually to ensure correct pattern of cell polarities	Machine vision check to ensure correct pattern of cell polarities
		Clean room conditions	Eliminate contaminants & water	Clean room like conditions	Clean room like conditions
3.1	Adhesive Dispensing	Pick top cell-insert	Speed	Human operator picks one top cell-insert from in-feed of top cell-inserts	Robot picks one top cell-insert from in-feed of top cell-inserts
	(top side of module)	Place top cell-insert on top end of cell stack	Precision & Speed	Human operator places top cell-insert on top end of cell stack	Robot places top cell-insert on top end of cell stack
		Change tool from cell-inert gripper to adhesive dispenser	Quick tool change	Not applicable	Robot quickly moves to tool changer and changes tool from gripper to adhesive dispenser
		Fill cell-wells with adhesive	Uniform application	Ensure all cell terminals get adhesive application	Robotic dispenser moves over battery module at a controlled predetermined speed.
			Fill all cell-wells with adhesive	Human operator fills all cell-wells in top cell-insert with adhesive	Robot should be able to reach all cell-wells and fill them with adhesive
			Complete filling	Human operator ensures that enough adhesive is dispensed to completely fill all spaces in the cell-well, between the cell and cell-insert structure	Robot dispensing speed ensures that enough adhesive is dispensed to completely fill all spaces in the cell-well, between the cell and cell-insert structure
		Change tool from adhesive dispenser to cell-insert gripper	Quick tool change	Not applicable	Robot quickly moves to tool changer and changes tool from adhesive dispenser to gripper
		Pick current collector plate from in-feed conveyor	Speed	Human operator picks one current collector plate from in-feed of current collector plate	Robot picks one current collector plate from in-feed
		Place connector plate on top of cell insert	Precision & Speed	Human operator places current collector plate on top of top cell-insert	Robot places current collector plate on top of top cell-insert
		Press connector plate on top of cell insert	Appropriate force application	Human operator holds and presses collector plate on top cell-insert so it bonds properly with adhesive	Robot appropriate pressure on collector plate so it bonds properly with adhesive

TABLE 7. (...Contd.) Steps for electric vehicle battery module assembly using cylindrical cells.

No.	Work Center	Manufacturing Step	Requirement	Manual	Automated
3.2	Adhesive Dispensing	Flip module to other side	Speed	Human operator flips battery module to bottom side using mechanism	Flipping mechanism flips battery module to other side
	(bottom side of module)	Extract cell-holding template from battery module	Speed	Human operator extracts the cell-holding template from the battery module	Robot extracts the cell-holding template from the battery module
		Place cell-holding template on used templates out-feed stack	Speed	Human operator places cell-holding template on out-feed stack of used templates	Robot places cell-holding template on out-feed stack of used templates
		Repeat all steps in 3.1 for for bottom end of battery module	Same as in steps in 3.1	Same as in steps in 3.1	Same as in steps in 3.1
4	Curing	Move adhesive bonded module to curing station	Heavy lifting (50 lbs)	Human picks and places module in curing station	Battery module is conveyed into curing station
			High voltage handling (22.5 V)	Human takes necessary precautions in handling high voltage	Robots assumes all risk of electric shock
5	Wire bonding	Place cured module in wire bonding machine	Heavy lifting (50 lbs)	Human picks and places module in wire bonding station	Robot picks and places module in wire bonding station
			High voltage handling (22.5 V)	Human takes necessary precautions in handling high voltage	Robots assumes all risk of electric shock
		Place wire bonded module in module housing	Heavy lifting (50 lbs)	Human picks and places wire bonded-module in battery module housing	Robot picks and places wire-bonded module in battery module housing
5	Components assembly	Install battery module control circuitry	Install small parts in tight spaces	Human fastens and secures module control circuitry in tight spaces using hand tools	Robotic automation may not have dexterity to perform this complex operation in tight spaces
		Install battery module cooling components	Install tubes and hoses in tight spaces	Human dexterity; Ability to handle flexible parts; Ability to work in small spaces	Robotic automation may not have the dexterity and adaptability to handle flexible workpieces
		Install battery module management system	Install small parts in tight spaces	Human fastens and secures module management system in tight spaces using hand tools	Robotic automation may not have dexterity to perform this complex operation in tight spaces
		Attach connecting wires to module terminals	Ability to handle flexible wires	Human dexterity and ability to handle flexible parts	Robotic automation may not have the dexterity and adaptability to handle flexible workpieces
		Final module quality check	Visual check	Human visually checks for completeness and any defects	Machine vision can do visual check
			Tightness check	Human tugs and pulls at connections and checks fasteners for secure connections	Robots not suitable for such operations
6	Module closeout	Pick module top cover and place on top of module	Speed and accuracy	Human places module cover on top of module	Robot picks and places module cover on top of battery module
		Bolt screws on top cover	Speed and accuracy	Human screws fasteners on cover to secure it to housing	Robot screws fasteners on cover to secure it to housing

manual assembly of components. Additionally, some inspection and testing of the battery module may be difficult to automate.

A study of the battery module assembly process also reveals a natural coalescing of the steps into the following distinct groups - cell stacking, adhesive dispensing, adhesive curing, wire bonding, manual assembly of components, and module closeout. We allocate the tasks into these work-cells and proceed to design an automation solution for each of the work cells. In what follows, we present the details of the process we follow to design the robotic work cells.

IX. ROBOTIC WORK-CELL DESIGN

To design the robotic work cell, we followed a systematic automation systems integration process. The steps in the design process are laid out in Fig. 25.

We start by first specifying the sequence of operations in each work cell. Next, we specify the process requirements for

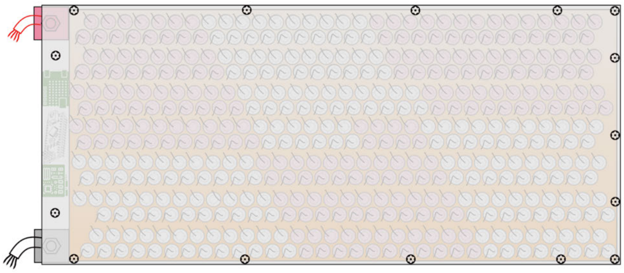

FIGURE 24. Sealed and bolted battery module ready for assembly in battery pack (top view).

each step under two categories - general and specific. Under general requirements we specify the standard requirements of reach, payload capacity, articulation, speed and precision. Under unique process requirements, we specify any requirements that are unique to a step. These process requirements are then translated into robot requirements which provide the lens through which different robot models are evaluated for that work-cell. After selecting the robots for a work-cell, we specify the other non-robotic components such as conveyors, end of arm tools and tool changers and other mechanisms.Using these artefacts, a design of the robotic work cell is specified.

In sections X - XIV, we provide the details of the process for designing automation for each of these work cells as well as the resulting designs of the robotic work cells.

X. CELL STACKING WORK CELL

The purpose of the cell stacking work cell is to take individual cylindrical cells and stack them into a desired pattern in the bottom cell-insert of the battery module. Creating a full battery pack for a single vehicle requires stacking several thousand individual cells and doing this manually can be very time consuming. Hence, this operation is an ideal candidate for robotic automation.

A. PROCESS DESCRIPTION AND REQUIREMENTS

The sequence of operations for stacking the cells is specified in Table. 8). The *general* and *specific* process requirements for the cell stacking operation are laid out in Tables. 9 and 10, respectively.

B. ROBOT REQUIREMENTS AND SELECTION

A careful study of the sequence of operations and the process requirements reveals that for cell stacking, a robot should have high speed, high precision and repeatability. Both SCARA robots (Fig. 26) and parallel linkage robots, also known as Delta robots (Fig. 27), meet these requirements.

Both SCARA and Delta robots have advantages and trade-offs associated with them. When considering the application speed requirements, Delta robots are typically capable of achieving the highest speeds. However, high speed and acceleration generate high inertia resulting in overshoot.

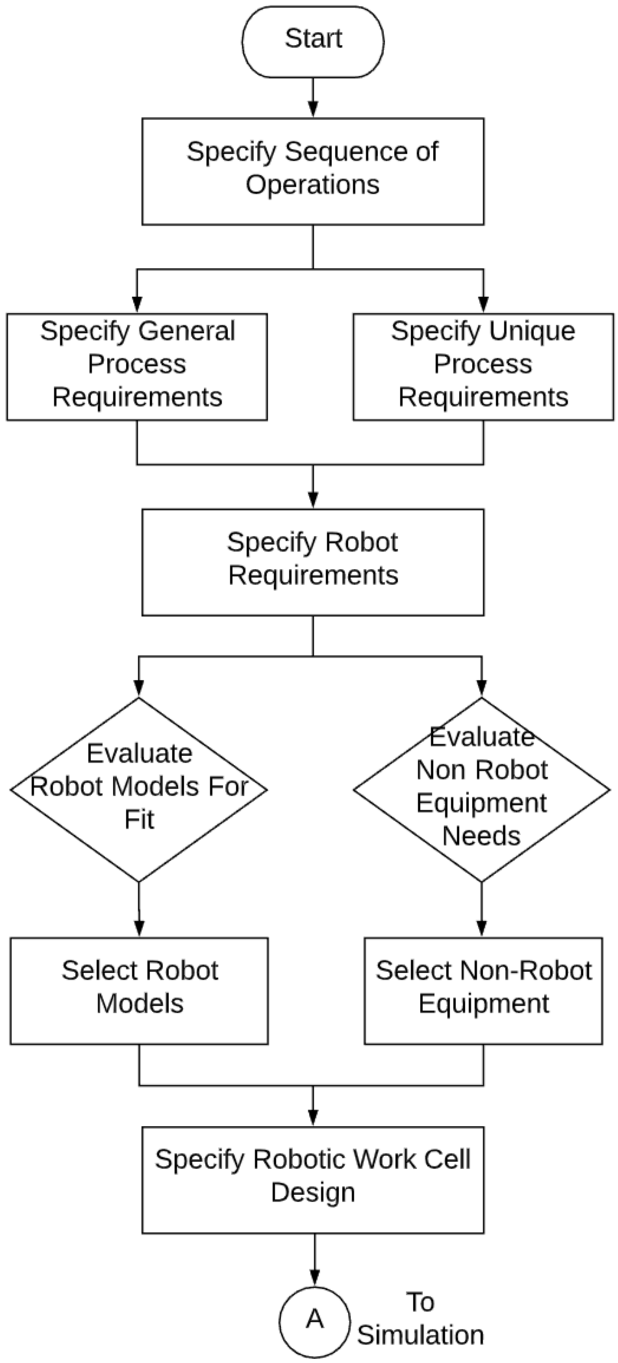

FIGURE 25. Robotic work cell design process.

Overshoot is the robot tool end point going beyond its desired destination point, especially at points where the direction of motion changes. For this reason, Delta robots may have to be operated at a speed below their theoretical maximum.

While SCARA robots have lower speed when compared to a Delta robot, they do have the advantage of higher precision owing to their serial linkage design. In a serial linkage design the X-Y location of the robot is only a factor of its first two axes, instead of three or more axes, as in the case of parallel-link robot models such as Delta robots. Additionally,

TABLE 8. Sequence of operations for cell stacking.

No.	Operation Step
1	Individual cells are conveyed through an inspection system which tests for voltage, leakage, dimensions and uniformity.
2	Each robot is fed cells on a pair of conveyors. One conveyor feeds cells with positive terminal facing up, and the other feeds cells with negative terminal facing up.
3	A machine vision camera does a final check for visible physical defects.
4	Batteries that pass the inspection are picked by the robot and vertically inserted into the cell-holding template.
5	The battery cells are picked and placed in the proper sequence to create the desired pattern of negative and positive cell polarities facing up in the battery module.
6	Once all the cells have been inserted in the battery module, it is released from the cell-stacking work cell and the next empty module indexes in.

TABLE 9. ***General*** **process requirements for cell stacking operation.**

Parameter	Requirement
Reach	Robot Work Envelop Should Cover Dimensions of the Battery Module = 26.9 in X 11.9 in
Payload	Robot should have sufficient payload capacity for individual cells (4.6 g) and weight of end effector (estimated at 5 lb)
Articulation	Minimum three degrees of freedom (X, Y, and Z).
Speed	Step is time consuming due to large number of pick and place (444/module) operations. High speed needed.
Precision	Precision of +/-0.15 mm is required.

TABLE 10. ***Unique*** **process requirements for cell stacking operation.**

No.	Requirement
1	During cell-insertion, robot should keep cell stable to prevent toppling over.
2	High speed tooling actuation to pick cells within 50 ms.
3	Robot motion path planning to ensure precise vertical entry of cells into holding-template holes.
4	Ability to accommodate positional randomness of cells on the in-feed conveyor.
5	Ability to reject visually defective cells that may have slipped through earlier quality checks.

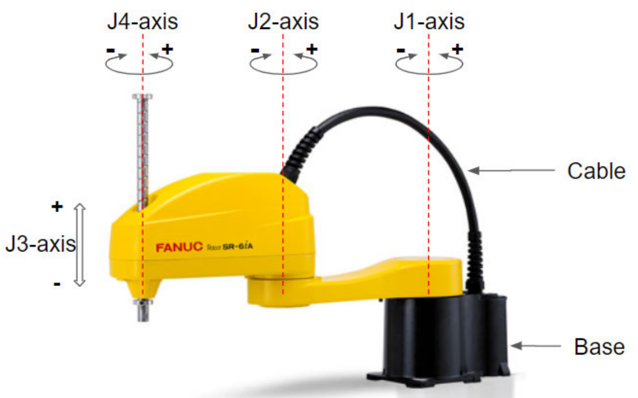

FIGURE 26. FANUC SR-6iA SCARA robot.

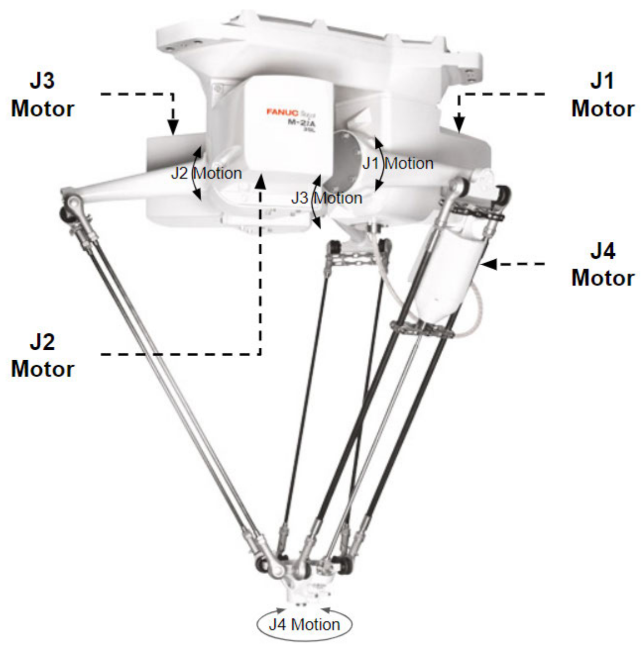

FIGURE 27. FANUC M-2iA/3SL parallel linkage delta robot.

the repeatability of a robot is also a function of its link length and the size of its work envelope. Generally, as robot reach increases, its repeatability decreases due to the increasing length of linkages between each axis. As the link length increases, the same deviation in link length can have an amplified effect on repeatability loss. For Delta robots this phenomenon becomes apparent as the link length between overhead-mounted motors and wrist can be quite large to afford a sizeable work envelope. SCARA robots on the other hand have relatively short linkages and a small work envelope, making them more repeatable than Delta robots.

Another factor that is of interest is the duty cycle of a robot which measures its ability to operate continuously at the specified speed and payload, without overheating of motors or premature mechanical failure of gears. The duty cycle of a robot is akin to a weightlifter lifting a weight, where only a certain amount of repetitions can be done before the weight lifter must rest to let their muscles recover. In a robot, if more heat is generated for a given motion than can be dissipated by the motor, the motor will eventually overheat and possibly fail. This can be managed by slowing down the motion, reducing the payload (which is usually not an option) or adding some rest periods to break down continuous motion.

Delta robots are especially suited for high-speed, high-duty cycle applications, because of their parallel linkages, which results in significantly less load on each motor. On the contrary, the mechanical linkages of a SCARA are serial in nature, with each axes' drive having to bear the load of all the subsequent axes' drives. This in turn reduces the duty cycle of a SCARA robot.

An advantage of a SCARA robot is its compact design resulting in a smaller footprint when compared to a Delta robot. Additionally, SCARA robots are one of the lowest cost robot models. A comparison of the two robots on critical factors is presented in Table 11.

In sum, both SCARA and Delta robot models are suitable candidates for the stacking work cell application, with their own unique advantages and disadvantages. We therefore present two cell-stacking work-cell designs, one using SCARA robots and the other using Delta robots. Most major robotic vendors have SCARA and Delta robots. Since this research collaboration was with FANUC America, we narrowed our search to their robots. We selected the FANUC SR-6iA SCARA robot and the FANUC M-2iA/3SL Delta robot, for our work-cell design. These work cell designs are now specified in detail.

C. CELL STACKING WORK-CELL DESIGN (USING SCARA ROBOTS)

The cell stacking work-cell consists of two FANUC SR-6iA robots. Each of these robots is fed vertically upright 18650 Li-Ion cells on a pair of conveyors (Fig. 28). One of the conveyors serves cells with the positive terminal facing up while the other conveyor serves cells with the negative terminal facing up. In the cell stacking process, the robot picks up cells from the appropriate in-feed conveyor based on whether the positive or negative terminal of the cell needs to be facing up for the next open position in the cell-insert.

A process design consideration is the very shallow depth of the cell-wells in the cell-insert. The cell inserts are sized such that the depth of the cell-wells is approximately 5-20% of the cell height [61]. Thus, only a small part of the cell gets inserted inside the cell-wells and there is a high probability of the cells toppling over while being inserted. To provide stability to the cells during the initial stages of the assembly process, a 'cell-holding-template', with holes corresponding to the cell-wells in the cell-insert, is used (Fig. 29).

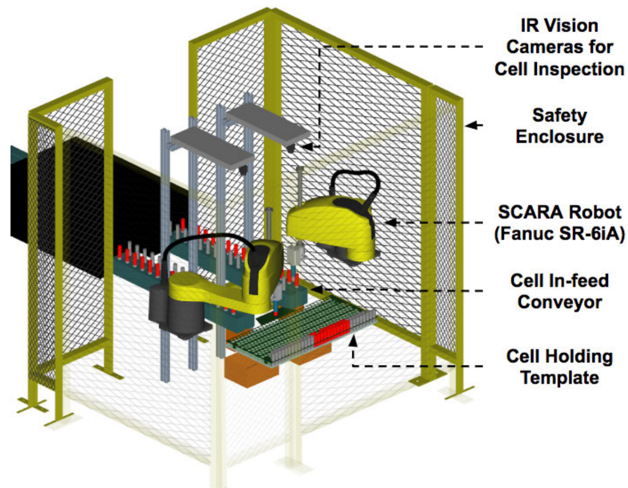

FIGURE 28. Cell stacking work cell using SCARA robots.

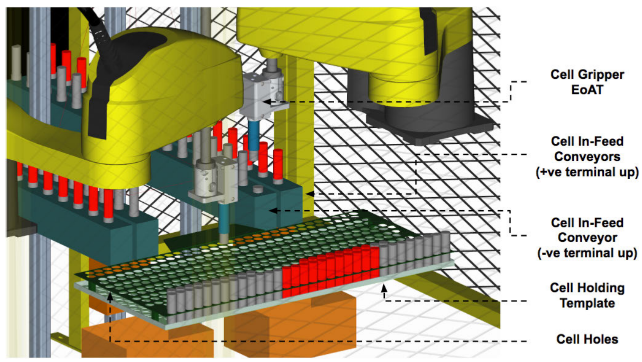

FIGURE 29. Cell holding template for cell stacking.

The holding-template serves as a temporary fixture to prevent the cells from toppling over, and is eventually removed from the battery module assembly.

Though the cells undergo multiple checks before they are fed onto the conveyors, the SCARA robots are integrated with a machine vision system that can do a final visual check for any physical defect before the robot picks up the cell. The camera is also used to accurately detect the location of the cell on the conveyor to account for any positional variance resulting from deviations in cell holding carrier or the position of the indexing conveyor. After a cell has passed the quality check of the machine vision system, the cells are fed to the robots in a vertically upright position to allow for easy gripping by the cell gripper end-of-arm tooling (EoAT).

The cell gripper is a cylindrical sleeve which fits around the cell from the top. A permanent magnet is actuated upwards and downwards on a pneumatic slide inside of the gripper. This magnet is separated from the cell at the top of the sleeve by a thin sheet of aluminum. When the magnet is in the lower position, it creates enough force on the cell to lift it up. When the magnet is actuated upward, further from the cell, the cell is released. Fig. 29 provides a close-up view of the cell gripper.

TABLE 11. Robot Requirements for cell stacking operation: A comparison of SCARA and delta robots.

Factor	SCARA (FANUC SR-6iA Robot)	Delta (FANUC M-2iA/3SL Robot)
Reach	**650 mm** - sufficient reach for this operation.	**1130 mm** - sufficient reach for this operation.
How many degrees of freedom	**Four axes** - sufficient for cell stacking	**Four axes** - sufficient for cell stacking
Payload	**6 kg** - sufficient payload capacity. Could not use 3 kg variant as it does not have sufficient reach.	**3 Kg** - sufficient payload capacity.
Repeatability/ accuracy	**± .01 mm** - sufficient for this operation.	**± .1 mm** - sufficient for this operation.
Speed	**[J1:440°/sec, J2:700°/sec, J3:2000mm/sec, J4:2500mm/sec]** For sustained operations, SCARA is slower than Delta. But, using two robots simultaneously reduces cycle time.	**[J4:3500°/sec]** Delta is the fastest robot - Overshoot due to high speeds can imply that speeds lower than theoretical maximum are used.
Duty Cycle	For long term sustained operation, to maintain reliability, Motor Duty (overheat) and reducer life (Gear wear and tear) need to be managed. Robotic simulation software, such as ROBOGUIDE can be used to determine the robot speed and rest periods to maintain reliable performance over the life time of the robot	Delta robots are designed for continuous operations and therefore motor Duty and gear life is not a prominent consideration.
Cost	**Low** - One of the lowest cost robot model	**High** - Delta robots are significantly costlier than SCARAs. The structure holding the Delta robot can add upto 20% of the cost of the robot.
Footprint	**Small**	**Large** - Delta robots have an exclusive work space that cannot be shared
Non robotic system components	Mounting pedestals. Are relatively cheap	The overhead structure of a Delta robot can add upto 20% of robot cost.

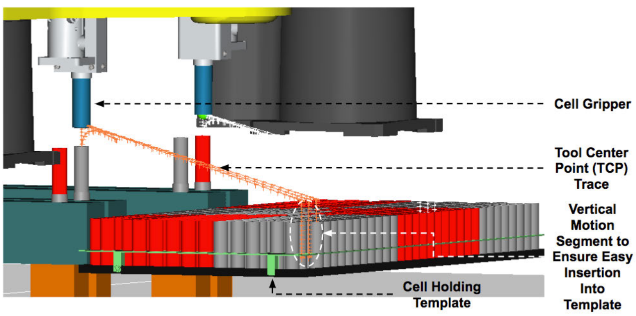

FIGURE 30. Tool path trace (TCP) of SCARA robot during cell stacking.

After the cell has been gripped, the robot arm picks it up and positions it accurately on top of the next holding-template hole into which it is to be inserted. To ensure precise insertion into holes, the robot is programmed to guarantee that the last segment of the insertion motion is vertical, as opposed to being rounded (Fig. 30). Having the conveyor and the cell holding template at the same level would require the robot arm to first get an initial vertical gain before descending to enter the holding template. Therefore, the conveyors are positioned slightly above the battery module so that a simple downward motion of the robot arm, positions the cell for easy insertion into the cell holes. This helps reduce both cycle time and wear and tear on the vertical axis of the robot.

Apart from cell stability, another important consideration in robot path planning is the prevention of collision between the robots or between cells while they are being inserted. To prevent interference with already stacked cells, the robots start inserting cells in the farther end and progressively move to the nearer end. This order of filling the cells ensures that there is no interference with existing cells when inserting a new cell in the module. To prevent interference of motion between robots, one of the robots starts inserting cells from one end of the module towards the middle of the module, while the other robot starts inserting cells from the middle of the module towards the other end. While these design choices prevent any interference, as an added safety measure, additional logical interlocks between the robots has been programmed to prevent them from colliding.

A total of 444 such pick and place motions are made for each battery module. Since we are using two SR-6iA robots, each robot makes 222 pick and place motions. Due to the large number of pick and place motions, even small non-essential movements of the robot can add significantly to the cycle time of the cell stacking operation. Hence, an important consideration in planning the robot paths is to optimize the trade-offs between considerations such as fast and short pick and place movements, overshoot due to fast movement, inaccurate placement of cells and collision avoidance. After all 444 cells have been inserted, the cell stacking step is completed. The battery module is then released to the next work cell for adhesive dispensing.

D. CELL STACKING WORK-CELL DESIGN (USING DELTA ROBOTS)

Because of how Delta robots are mechanically constructed, they need a structure to hold them. Fig. 31 illustrates a Delta robot suspended from an overhead structure.

The rigidity of this overhead structure is critical, as vibrations resulting from robot movements will lead to a loss of accuracy and may also effect the durability of the robot itself. Typically, Delta robot manufacturers provide the natural frequency, force and moments that act on the robot base to allow for design of a rigid enough structure. We used

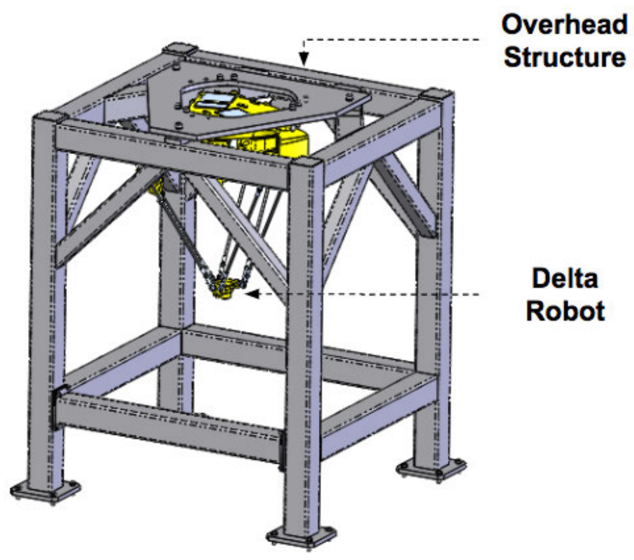

FIGURE 31. Overhead structure for supporting delta robots.

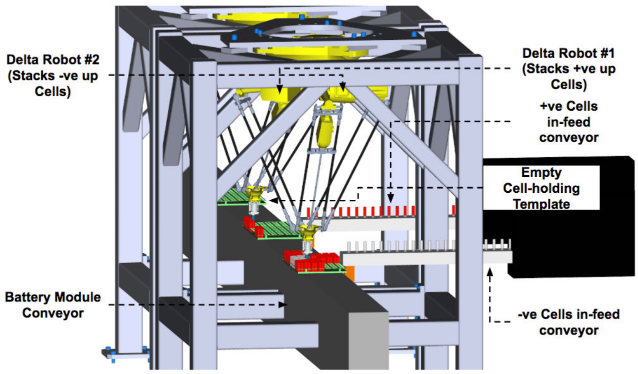

FIGURE 32. Cell stacking work cell using delta robots.

these specifications in designing the overhead structures for the work cell. Because of this overhead structure and robot construction, each robot has its own exclusive work envelop which cannot be shared with another robot. For this reason, unlike the SCARA configuration, Delta robots cannot stack cells in the same module simultaneously.

In the cell assembly work-cell using Delta robots, two FANUC M-2iA/3SL Delta robots are positioned one after the other, over a conveyor belt which carries the battery module (Fig. 32). Each of the Delta robots is fed cells in a vertically upright position on a conveyor. The first Delta robot is fed cells with the positive terminal facing up, while the second Delta robot is fed cells with the negative terminal facing up. The cells are fed in a vertically upright position to allow for easy gripping by the battery cell gripper end-of-arm tooling (Fig. 33).

The first Delta robot inserts all the cells with the positive terminal facing up. Once the first robot completes inserting all the positive facing up cells, the conveyor moves the battery module forward to be placed under the second Delta robot. Simultaneously, A new completely empty battery module indexes in under the first Delta robot which then

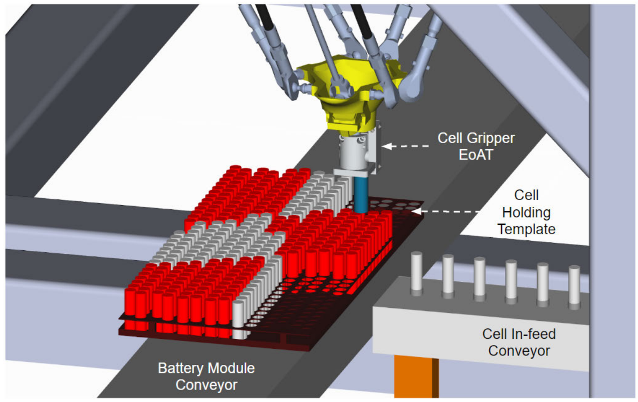

FIGURE 33. Cell stacking work cell using delta robots (close-up view).

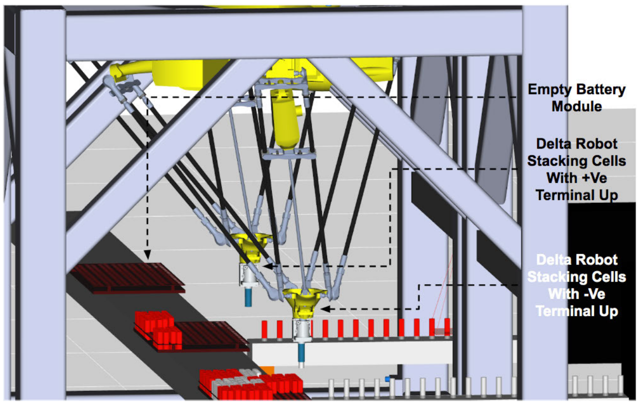

FIGURE 34. Cell stacking work cell using delta robots.

starts inserting cells with their positive terminals facing up in it. The second Delta robot now stacks cells with their negative terminal facing up in the remaining cell holes of the first module. This simultaneous assembly of two modules by the Delta robots helps keep the cycle time down and is illustrated in Fig. 34. While designing the cell-stacking work-cell using Delta robots, we took into account process design considerations similar to the SCARA work cell. We incorporate the use of a cell-holding template to account for the shallow cell-well depth, robot path planning to prevent collisions between cells, and, cell quality checks using machine vision cameras.

A process design consideration unique to Delta robots is accounting for overshoot when moving at high speed. Delta robots are one of the fastest robots and overshoot problems have been reported from the field. Hence, while designing the work-cell, we were careful to not operate the Delta robot at its maximum theoretical speed for motions that required high precision. Examples of such motion are rounding downward while approaching each cell's drop location. Motions such as retracting from the drop location can be done at a higher, or even maximum robot speed as any overshoot will not affect the overall process.

A total of 444 pick and place motions are made for each battery module. Since we are using two M-2iA/3SL robots,

TABLE 12. Sequence of operations for adhesive dispensing work cell.

No.	Operation
1	Cell-holding template with stacked cells is conveyed into the adhesive dispensing work-cell and clamped in and secured inside the module holding and flipping mechanism.
2	Robot picks and places the top cell-insert on the top end of the stacked cells.
3	Robot moves to tool changer and switches from gripper to adhesive-dispenser end-of-arm tool (EoAT).
4	Robot dispenses Loctite adhesive into the cell-wells of the top cell-insert.
5	Robot moves to tool changer and switches back from adhesive-dispenser to gripper EoAT.
6	Robot picks the current collector plate and places it on top of the top cell-insert.
7	Robot holds and presses down on current collector plate with small force to ensure proper bonding.
8	Flipping mechanism flips the battery module over to the bottom side.
9	Robot removes the cell-holding template from the battery module and places it in a bin for later removal from the work-cell.
10	Robot picks and places the bottom cell-insert on the bottom end of the stacked cells in the battery module.
11	Robot moves to tool changer and switches from gripper to adhesive-dispenser EoAT.
12	Robot dispenses Loctite adhesive into the cell-wells of the bottom cell-insert.
13	Robot moves to tool changer and switches back from adhesive-dispenser to gripper EoAT.
14	Robot picks the current collector plate and places it on top of the bottom cell-insert.
15	Robot holds and presses down on current collector plate with small force to ensure proper bonding.
16	Adhesive bonded battery module is released from the work-cell and is sent to curing area.

TABLE 13. ***General*** **process requirements for adhesive dispensing work cell.**

Parameter	Requirement
Reach	Robot work envelop should cover the extremeties of the work areas of the adhesive dispensing work cell (1.5 m X .8 m).)
Payload	Robot should have sufficient payload capacity(~2kg). The total payload is weight of end-of-arm tooling (1Kg), maximum weight of workpieces (0.5 kg) and weight of tool changer (0.5 kg).
Articulation	A 6th axis articulation is NOT needed.
Speed	The adhesive needs to be dispensed at a sufficiently slow pace to ensure that proper filling of spaces occurs. Additionally, while handling flexible parts such as the current collector plate, slower speeds are advised. Consequently, high robot speed is not a requirement.
Precision	A precision of .02 mm is sufficient for the adhesive dispensing operation.

TABLE 14. ***Unique*** **process requirements for adhesive dispensing work cell.**

No.	Requirement
1	Adhesive should fill all the spaces and interstices between the cell and the cell-insert structure, inside the cell-well.
2	Adhesive should be dispensed at a consistent and uniform rate.
3	Tool changing system is required because the same robot is doing pick and place and adhesive dispensing.

each robot makes 222 pick and place motions. Due to the large number of pick and place motions, even small non-essential movements of the robot can add significantly to the cycle time of the cell stacking operation. Therefore, a very important consideration in planning the robot paths is to optimize the trade-offs between considerations such as fast and short pick and place movements, overshoot due to fast movement, inaccurate placement of cells and collision avoidance. After all 444 cells have been inserted, the cell stacking step is completed. This assembled battery module is then conveyed to the next work cell for adhesive dispensing.

XI. ADHESIVE DISPENSING WORK CELL

The purpose of the adhesive dispensing work cell is to bond cell inserts and current collector plates on both ends of the battery module. The cell-inserts and the collector plates are bonded to the module structure using an adhesive such as Loctite. The adhesive is dispensed in the cell-wells such that it fills up the spaces remaining between the cell and the cell-insert structure. Sufficient adhesive is dispensed inside the cell-wells so that in addition to bonding the module members, it also provides structural strength and integrity to the battery module.

A. PROCESS DESCRIPTION AND REQUIREMENTS

The sequence of operations for adhesive dispensing is specified in Table 12. The *general* and *specific* process requirements for adhesive dispensing work-cell are specified in Tables 13 and 14 respectively.

B. ROBOT REQUIREMENTS AND SELECTION

A review of the sequence of operations in the adhesive dispensing work cell clearly indicates that a variety of tasks need to be completed. In addition to dispensing the adhesive, the robot also needs to pick and place module components such as cell inserts and collector plates. These two operations require different End of Arm Tools(EoAT). The adhesive operation requires a dispensing nozzle, while the pick and place operation requires a vacuum gripper. We considered

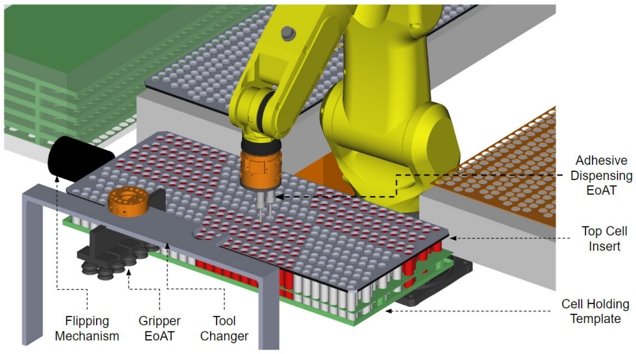

FIGURE 35. Adhesive dispensing work cell (close-up view).

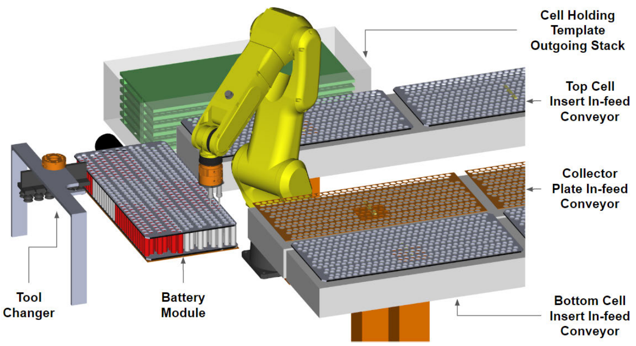

FIGURE 36. Adhesive dispensing work cell work areas.

the option to use separate robots for these two operations. On further analysis, we found it more economical to use a single robot to do both these operations by including a tool changing mechanism (Fig. 35).

In addition to accessing the tool changer, the robot also needs to pick work pieces from four in-feed conveyors - one each for the top and bottom cell-insert, one for the collector plate and one for the battery module itself. Because of the need to reach multiple work areas, a robot with a large work envelop is required. Fig. 36 illustrates the different work areas of the adhesive work cell.

The limiting factor for this operation is the speed at which the dispensing applicator can be moved while still dispensing a sufficient and consistent amount of adhesive into each of the wells. Because of this the robot does not need to move quickly, and the required speed is well within the capability of most robot models. Hence robot speed is not a major consideration in robot selection for this work cell.

Another requirement for this operation is the ability to dispense the adhesive uniformly in all the cell-wells to prevent over or under filling resulting in a variation in the structure of the battery. To achieve this, the robot must have high precision and repeatability. Finally, while placing the cell inserts and plates at the ends of the module, the robot should be able to apply pressure against the adhesive to secure proper bonding. This requires the robot to have sufficient wrist force.

All these requirements can be met with an articulated robot. Most major robotic vendors have articulated robots. In consultation with our panel of automation experts we chose to use

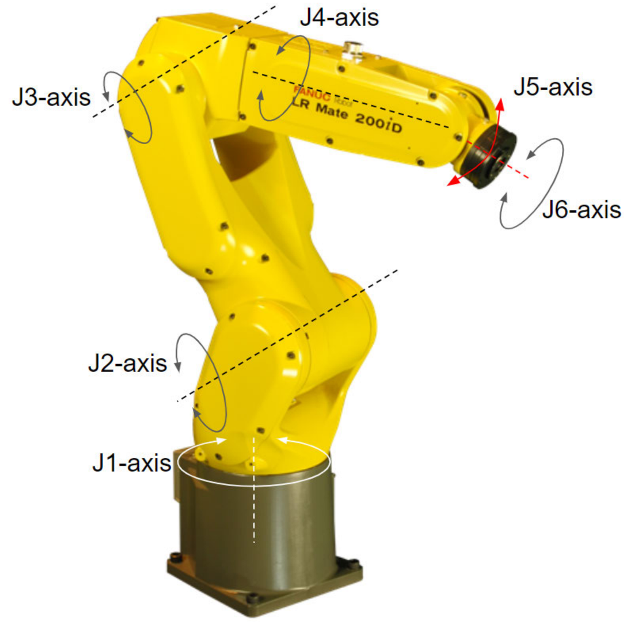

FIGURE 37. FANUC LR Mate 200iD articulated robot.

FANUC's LR Mate 200iD/7L articulated robot (Fig. 37). The 'L' at the end of the model name indicates the long-arm version of the standard LR Mate 200iD model, which increases the reach. This larger reach and work envelop affords greater flexibility in laying out the different work areas of the work-cell. Also, the larger vertical stroke of the LR Mate when compared to a Delta or a SCARA robot, provides flexibility in locating the tool changing mechanism above any conveyance system into or out of the work-cell. Finally, the availability of a sixth axis of articulation in the LR Mate robot provides for any flexibility and fine tuning of motion that may be required to successfully assemble the plastic inserts or collector plates onto the module. The Delta and SCARA robots only have four axes which precludes such flexibility in case it is needed. A summary of the LR Mate 200iD/7L robot parameters on critical factors is presented in Table 15.

C. ADHESIVE DISPENSING WORK-CELL DESIGN

The adhesive dispensing work cell receives the battery module from the cell stacking work cell. In this partially assembled state, the structural strength of the battery module is provided by the cell holding template fixture. To ensure the structural integrity of the battery module during the adhesive dispensing operation, additional reinforcement is needed. This structural reinforcement is incorporated into a module flipping mechanism. This flipping mechanism serves two essential functions. First it securely holds the stack of cells in place while the adhesive is dispensed and while the cell inserts are applied. Secondly, its motor rotates to flip over the module to provide access to both the top and bottom sides of the battery module. This is required since the operations in the adhesive dispensing work cell are executed on both sides of the module.

TABLE 15. Robot requirements for adhesive dispensing operation: Evaluation of an articulated robot.

Factor	FANUC LR Mate 200iD/7L Articulated Robot
Reach	**911 mm** - We used the long arm version of the robot for longer reach. This reach is sufficient for this operation.
Articulation	**Six axes** - only four degrees of freedom is required for the operation.
Payload	**7kg** - 7 Kg is sufficient payload capacity for this operation.
Repeatability/ accuracy	**± .01 mm** - This level of precision is sufficient for this operation.
Speed	Robot speed is not a concern (speed of adhesive dispensing is the limiting factor).
Duty Cycle	For long term sustained operation, to maintain reliability, motor duty (overheat) and reducer life (Gear wear and tear) need to be managed. The required speed and payload for adhesive dispensing is fairly low and hence duty cycle is not a concern.
Cost	**Moderate**
Footprint	**Small**
Non robotic system components	Flipping Mechanism consisting of a FANUC servo motor and a holding fixture ;Tool changer; Conveyors for feeding cell-inserts and the current-collector plate.

Once the module enters the work cell, and is secured to the flipping mechanism, the robot picks and places a top cell-insert on top of the cells using a gripper end of arm tool. The robot then moves to a tool changer where it switches to an adhesive-dispensing tool head.

The robot then moves this adhesive dispensing tool head over the module to dispense Loctite adhesive into the cell-wells. The adhesive is dispensed to fill the remaining space within the cell-wells of the battery module. The robot movement is maintained at 150mm/s while the adhesive is being dispensed to achieve proper filling up of the adhesive.The dispenser has two nozzles for dispensing the adhesive, which reduces the number of passes from 14 to seven in order to fill all the cell-wells.

Once the adhesive is applied, the robot revisits the tool changer to switch back to the gripper EoAT. The robot then picks up the current collector plate and places it on the top cell-insert. The robot then gently presses the collector plate on top of the cell-insert to ensure proper bonding between the collector plate and the cell-insert. Once the collector plate has been attached to the top side of the module, the robot moves out of the way and the flipping mechanism motor rotates to flip the module to expose the bottom side of the module. At this point, the robot extracts the cell holding-template from the battery module using the gripper, and places it in a bin for later removal from the work-cell. These holding-templates serve as a temporary fixture for structural support and can be reused.

The robot now proceeds to repeat the same sequence of operations on the bottom side of the module as it executed on the top side. This completes the operations in the adhesive dispensing work-cell and the module is released from the flipping mechanism and sent to a curing area for the adhesive to cure. Once the adhesive has cured, it provides additional mechanical reinforcement and adds to the structural strength of the battery module. After the curing operation, the battery module is conveyed to the wire bonding work-cell.

XII. WIRE BONDING WORK CELL

The purpose of the wire bonding work-cell is to connect the individual cell terminals to the current collector plates using Aluminium fuse wires. In wire bonding, a metallic wire is press-fitted on a metallic substrate using pressure and ultrasonic power to create a connection between the two metals. The cell terminals on the top side of the module are connected to the top plate, while the cell terminals on the bottom side are connected to the bottom plate. These plates in turn carry the current to the module terminals, which are a pair of M8 bolts (Fig. 9).

Because individual connections are made between the terminals and the current collector plate, the wire bonding process is time consuming. Hence, in configuring the wire bonding work cell we have used two wire bonding machines.

A. PROCESS DESCRIPTION AND REQUIREMENTS

The wire bonding sequence of operations is specified in Table 16. The *general* and *specific* process requirements for wire bonding work-cell are specified in Tables 17 and 18 respectively.

B. ROBOT REQUIREMENTS AND SELECTION

In the wire bonding work-cell, the robot performs the job of picking and placing the battery modules into the wire bonding machines. Additionally, the robot needs to retract the wire bonded battery module from the machine and place it in the battery module housing structure. Since the robot needs to reach both the wire bonding machines as well as the battery module housing, it needs to have a long reach.

A second requirement of the robot is six-axis articulation. Once the cell terminals on one side of the module have been wire bonded, the battery module needs to be flipped over to wire bond the other side. Because of this need to flip the battery module, a six-axis articulated robot is needed (Figure 38). A third requirement of the robot is sufficient payload capacity to pick up a 50 lb battery module while also accounting for the EoAT gripper weight. Because the majority of the time is taken up by the wire bonding process, robot speed is not a consideration for this work cell.

A final consideration which is out of scope of this study is the gripper design. The battery module at the wire bonding

TABLE 16. Sequence of operations for wire bonding work cell.

No.	Requirement
1	Adhesive bonded battery modules are conveyed into the wire bonding work cell.
2	Robot picks up a battery module and places it into the first wire bonding machine, with its top end facing up.
3	Robot picks up another battery module and places it in the second wire bonding machine, with its top end facing up.
4	The wire bonding machines start wire-bonding fuse wires between each cell terminal and the top current collector plate.
5	Once all the cell terminals on the top end of the battery module have been wire bonded to the top current collector plate, the robot reaches into the machine , picks up the battery module, flips it, and places it back into the wire bonding machine with the bottom side of the module facing up.
6	The wire bonding machine now starts wire-bonding fuse wires between cell terminals on the bottom side of the module and the bottom current collector plate.
7	Once all the cell terminals on the bottom end of the battery module have been wire bonded to the bottom current collector plate, the robot reaches into the machine , picks up the battery module, and places it into an empty battery module housing available on an out-feed conveyor.
8	This battery module housing with the module inside it, then exits out of the wire-bonding work cell on a conveyor that takes it to the manual assembly work station.

TABLE 17. ***General*** **process requirements for wire bonding.**

Parameter	Requirement
Reach	Robot work envelop should cover the work areas of the work cell. For the given work cell design with two wire bonding machines, the required reach is in the range of 2m X 2m.)
Payload	Robot should have sufficient payload capacity to pick up the battery module 50 lbs.
Articulation	A sixth axis articulation is required since we need to be able to flip the battery module.
Speed	Wire bonding is a time consuming process and determines the cycle time of the operation. Consequently, the speed of the robot is not a limiting factor and is not critical for this work cell.
Precision	Since in this work-cell, the robot performs a general pick and place operation of the battery module, precision of the robot is not that critical.

TABLE 18. ***Unique*** **process requirements for wire bonding.**

No.	Requirement
1	There is very tight tolerance between the battery module and the battery housing. This may prevent the use of mechanical side grippers when placing the module inside the housing. Therefore dual grippers are needed. Mechanical grippers are needed for picking the module for placement into the wire-bonding machine. Vacuum grippers are needed when inserting the battery module inside the module housing.

stage is partially assembled and lacks sufficient structural strength. The vertical stack of 444 cells is held together only by the cell inserts and the adhesive and there is a risk of the cells falling apart. Therefore, a key requirement is a gripper design that ensures the structural stability of the battery module while it is being picked and flipped over for placement in the wire bonding machine. Our proposed solution is using a gripper design that combines both mechanical and vacuum actuation as illustrated in Fig. 39. Similar dual mode grippers have been designed and used successfully in robotic palletizing applications [60].

Based on these requirements, we selected FANUC's M-710iC/50 articulated robot model as it provides sufficient reach to complete all operations as well as a sixth axis articulation (Fig. 40). Additionally, its payload capacity is capable of handling the weight of the battery module as well as the gripper weight. A summary of the robot parameters on critical factors is presented in Table 19.

C. WIRE BONDING WORK CELL DESIGN

The Wire bonding work cell consists of two wire bonding machines, a pick and place robot, specialized grippers, a tool changer, an in-feed conveyor to bring in adhesive bonded and cured battery modules, and, an out-feed conveyor to dispatch wire bonded modules. A layout of the work cell is provided in Fig. 41.

Once the battery module is received in the wire bonding work-cell, the robot picks the module and places it in the wire bonding machine such that the top end of the module is facing up. The wire bonding machine then starts to fuse wires between the cell terminals and the current collector plate. A connection to the cell terminals is possible because the cell terminals are exposed and available for bonding since the holes in the cell-insert as well as in the collector plate are aligned with the cell terminal ends (Fig. 14).

Once the top terminals of all 444 cells have been connected, the robot takes the module out of the wire bonding machine, flips it and places it back inside the machine such that the bottom end of the module is now facing up. At this point, the bottom side of the module is available for wire bonding. The machine repeats the wire bonding process for the bottom terminals of the 444 cells in the module. Once all the cells have been wire bonded, the robot picks the module and places it into an empty module housing structure that is

TABLE 19. Robot requirements for wire bonding: Evaluating an articulated robot.

Factor	FANUC M-710iC/50 Articulated Robot
Reach	**2050 mm** - Sufficient for this operation.
Articulation	**Six Axes** - Sixth axis articulation is required for flipping the module.
Payload	**50 kg** - This is sufficient for the battery (50 lb) and the end of arm tool.
Repeatability/ accuracy	± **.03 mm** - This precision is sufficient for this operation. Robot precision is not that critical for this operation.
Speed	Robot speed is not a consideration
Duty Cycle	For long term sustained operation, to maintain reliability, Motor Duty (overheat) and reducer life (Gear wear and tear) need to be managed. Robotic simulation software can be used to determine the robot speed and rest periods to maintain reliable performance over the life time of the robot.
Cost	**Moderate**
Footprint	**Medium**
Non robotic system components	Wire bonding machines ; In-feed and Out-feed Conveyors.

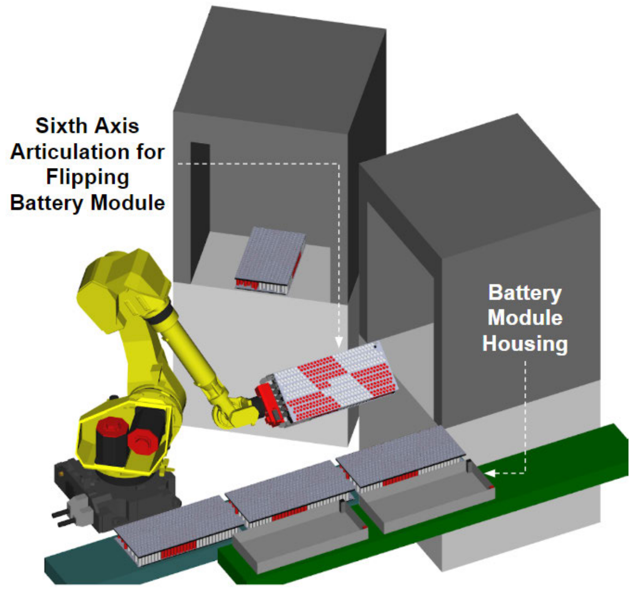

FIGURE 38. Wire bonding robot sixth axis articulation.

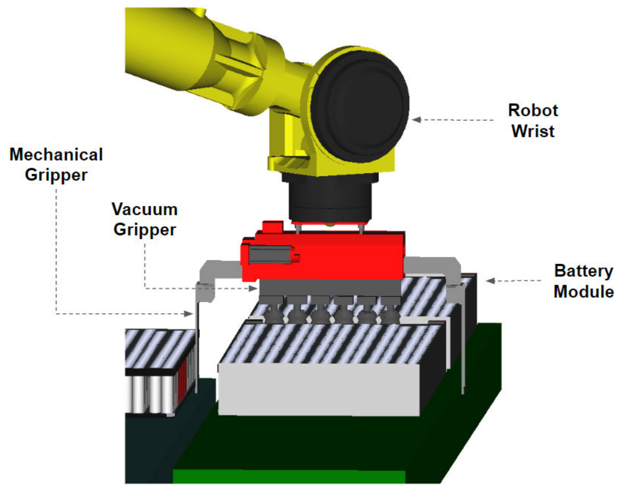

FIGURE 39. Wire bonding robot dual gripper.

available on an out-feed conveyor. Once the module is placed inside the housing, it is released for conveyance to the manual assembly workstation.

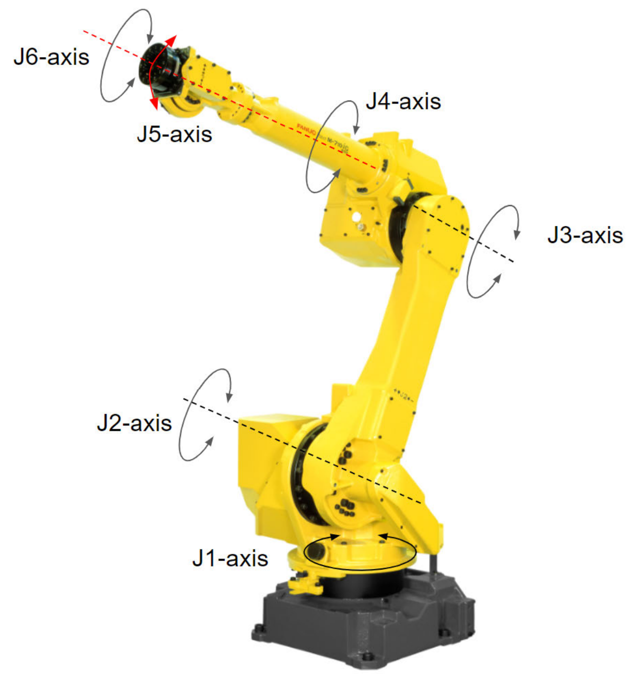

FIGURE 40. FANUC M-710iC/50 articulated robot.

XIII. MANUAL ASSEMBLY WORK STATION

The purpose of the manual assembly work station is to install, inside the battery module housing, components such as the module controller, thermal management system components, electronic parts, wires, cables and hoses. A close study of battery tear down videos reveals that this step requires assembling components into tight, hard to reach spaces,and handling flexible parts such as wires and hoses. On consultation with robotic automation experts, we determined that these steps are not amenable to automation and must be completed by a human operator.

XIV. MODULE CLOSEOUT WORK CELL

The purpose of the Module closeout work cell is to place a cover on the battery module housing and seal and bolt it up. At this point the battery module is ready to be used in assembling the battery pack. This work cell requires two

TABLE 20. Sequence of operations for module close out work cell.

No.	Requirement
1	Wire-bonded and manually assembled battery modules are conveyed into the module close-out work cell.
2	The robot picks the battery module housing cover and places it on top of the bottom member of the battery module housing structure.
3	The screw runner robot then drives screws into the screw holes.
4	The closed and completed battery module is conveyed out of the close-out work cell to a storage area.

TABLE 21. ***General*** **process requirements for module close out (*****cover placement*****).**

Parameter	Requirement
Reach	For battery module cover placement, the required reach is approximately 15 inches.
Payload	The module cover is light weight and hence robot payload capacity is not a concern.
Articulation	Module cover placement is a simple pick and place operation. A sixth axis articulation is not needed.
Speed	The operation subsequent to cover placement is cover screwing. Cover screwing is a time consuming process. For this reason, the speed of cover placement is not a limiting factor. Thus, robot speed is not critical.
Precision	The module cover must be placed precisely so the screw holes in the top cover and bottom member are aligned accurately. A precision of 0.2 mm is sufficient for this application. Additionally, machine vision can be used to precisely place the cover on top of the bottom member such that the holes are aligned.

TABLE 22. ***General*** **process requirements for module close out (*****cover screwing*****).**

Parameter	Requirement
Reach	For driving screws into the battery module cover, the robot work envelop should cover the dimensions of the battery module = 26.9 in X 11.9 in
Torque	Articulated robots can handle the torque required for fastening screws into the battery module.
Articulation	Screw driving operation does not require a sixth axis articulation.
Speed	The time consuming part of this operation is driving the screws in the holes. For this reason the speed of the robot movement is not a limiting factor.
Precision	The screw runner robot needs to have high precision to accurately position the screws over the holes. A precision of 0.2 mm is sufficient for this operation.

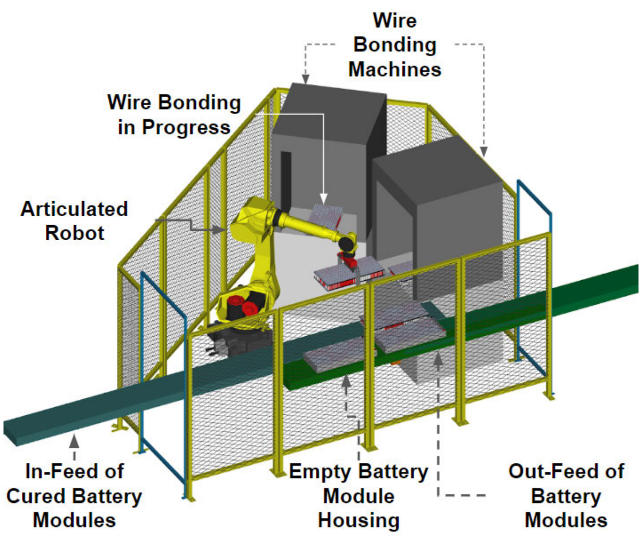

FIGURE 41. Wire bonding work cell layout.

operations: picking and placing the battery cover on top of the module housing structure, and fastening the battery cover to the bottom part of the module housing using screws.

A. PROCESS DESCRIPTION AND REQUIREMENTS

The module closeout sequence of operations is specified in Table 20. The *general* and *specific* process requirements for the module closeout work cell are specified in Tables 22 and 23 respectively.

B. ROBOT REQUIREMENTS AND SELECTION

There are two operations that are executed in the module close out work cell: (a) a pick and place operation to place the battery cover on top of the bottom part of the module housing structure (b) Running screws through the screw holes to secure the battery cover to the module housing. We considered the possibility of doing both the steps using a single robot and a tool changing mechanism. However, the screw running robot has a specialized screw feed mechanism which is not amenable to being swapped in a tool changing mechanism. Hence we had to use separate robots for each of these operations. A layout of the module close out work-cell is illustrated in Fig. 42.

Placing the module cover is a simple pick and place operation. The required reach, speed and payload capacity of the robot is small. Thus, we have selected the FANUC LR Mate 200iD robot, which meets all these requirements for this operation.

The screw running robot needs access to the full area of the battery module in order to drive in the screws. Therefore a larger work envelop area is required. Another consideration for the screw driving operation is the torquing ability of the robot. While both SCARA and articulated robots allow for the

TABLE 23. ***Unique*** **process requirements for module close out (*cover screwing*).**

No.	Requirement
1	The screw driving tool needs to be mounted at 90 degrees to the wrist flange or the 6th axis. This perpendicular mounting ensures that the torque exhibited during the screw driving operation is borne by the major axes and the base of the robot as opposed to the wrist axis which is smaller and less tolerant to the torque.

TABLE 24. **Robot requirements for module close out (*cover placement*).**

Factor	FANUC LR Mate 200iD Articulated Robot
Reach	**717 mm** - This is sufficient reach for this operation.
Articulation	**Six axes** - Only three degrees of freedom are needed for this operation. A SCARA robot could have been used. We have used an articulated robot for retaining the flexibility to tend to multiple screw running robots, if needed.
Payload	**7 Kg** - This is sufficient payload capacity for the module top cover
Repeatability/ accuracy	$\pm$ **.01 mm** - This is sufficient precision for this operation.
Speed	Speed of robot is not a consideration for this step.
Duty Cycle	Module cover is light weight and hence duty cycle is not a concern for this operation.
Cost	**Moderate**
Footprint	**Small**
Non robotic system components	In-feed and Out-feed conveyors.

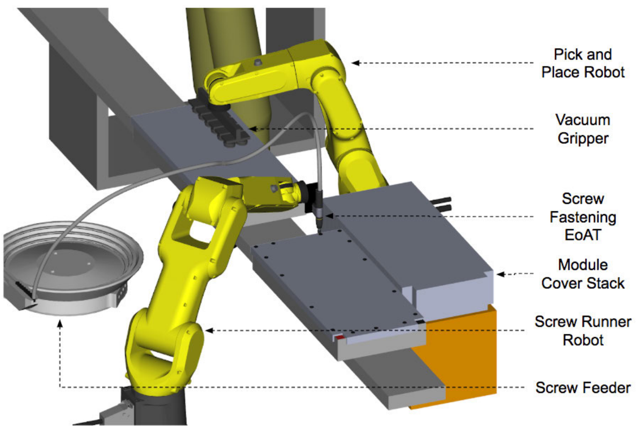

FIGURE 42. **Module close out work cell.**

application of high torque, articulated robots are able to fasten the maximum range of screw dimensions and screw materials. This is so, because, for an articulated robot, the screw driving tool can be mounted perpendicular to the robot wrist axes, allowing the larger first(J1), second(J2) and third(J3) axes to experience the bulk of the torque from the screw driving operation.

Precision is another critical factor for screw running. The screws need to be positioned precisely over the holes to prevent bending or breakage during fastening. A precision of +/− 0.2 mm or less is desirable for this application.

Robot speed is not a critical factor in this application. The major share of time is taken in driving the screws into the holes. Moving from one hole to another is a very small fraction of the total time taken. Consequently, the speed of screwing is more critical than the speed of motion of the robotic arm. The speed of driving the screw depends upon the end-of-arm tooling for screw driving. Therefore, from a robot selection perspective, robot speed is not a critical factor.

In sum, a screw running robot for this work cell should have large reach, high precision and high torquing ability. Based on these requirements, we considered both the FANUC LR Mate and SCARA robot models. We selected the FANUC LR Mate 200iD/7L articulated robot model as it provides the optimal torquing ability for effective running of the screws. Also, the letter 'L' at the end of the model indicates that we have chosen a long arm version of the robot which helps achieve the desired reach. Finally, the LR Mate 200iD/7L robot model provides a precision of +/−.01 mm which is well within the precision of +/−.2 mm required for screw running. A summary of the robot parameters on critical factors is presented in Table 25.

C. MODULE CLOSE OUT WORK CELL DESIGN

The module close out work cell consists of a FANUC LRMate 200iD robot for pick and place, and a FANUC LRMate 200iD/L robot for screw running. In addition, the work cell contains, a stack of battery module top covers, a conveyor for moving the module through the work cell, and, a screw feeding mechanism that supplies screws to the screw runner robot. A layout of the close out work cell is provided in Fig. 43.

An in-feed conveyor brings in the battery module from the manual assembly workstation to the module close out work-cell. Once the battery module comes in, the pick and place robot picks up the battery module housing cover and places it on top of the battery module housing. This placement has to be made precisely so that the screw holes in the battery module housing cover and the bottom housing structure align properly. After placement of the housing cover, the conveyor carries the module to under the screw running robot. The screw fastening robot drives in screws into the screw holes on the top cover. At this step as well, precision is critical to prevent bending or breakage of screws as they are driven

TABLE 25. Robot requirements for module close out (*cover screwing*).

Factor	FANUC LR Mate 200iD/7L Articulated Robot
Reach	**911 mm** - We used the long arm version of the robot for longer reach. This reach is sufficient for this operation.
Articulation	**Six axes** - only four degrees of freedom is required for this operation.
Payload	**7 kg** - Screws are light and payload is not a consideration for this operation. However, the ability to generate sufficient torque for screwing is important. Because of this consideration, we use an articulated robot instead of a SCARA robot, as it offers much better torquing ability for screwing.
Repeatability/ accuracy	**± .01 mm** - A precision of 0.2 mm is sufficient for this operation.
Speed	The time consuming part of this operation is driving the screws in the holes. For this reason the speed of the robot movementis not a limiting factor.
Duty Cycle	For long term sustained operation, to maintain reliability, motor duty (overheat) and reducer life (Gearwear and tear) need to be managed. Even though the screw weight is not significant, the force generated due to torquing needs to be taken into consideration. The duty cycle of the robot can be determined using robotic simulation software.
Cost	**Moderate**
Footprint	**Small**
Non robotic system components	Screw feeder; Screw driving EoAT

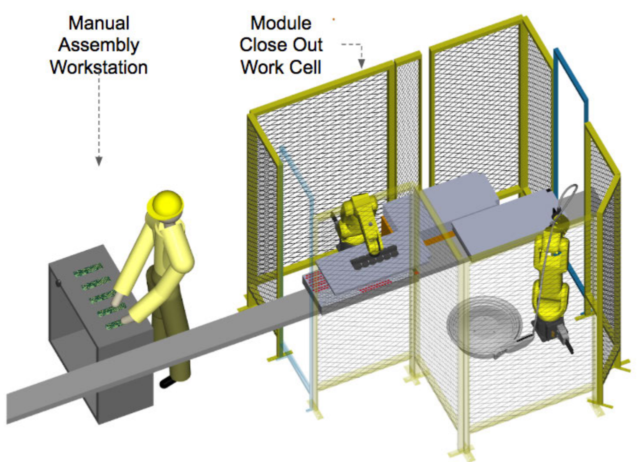

FIGURE 43. Manual assembly work station and module close out work cell.

into the holes. Once all the screws have been driven into the module housing cover, the assembly of the battery module is complete. The module is then conveyed out of the closeout work station, ready to be used in assembling battery packs.

XV. SIMULATION

One of the key objectives of this research project is to propose robotic automation solutions that can be realistically used by EV battery system manufacturers for fast and reliable assembly of high quality battery modules at scale. While it is possible to evaluate robotic automation solutions by setting up physical prototype work-cells, it can be a highly expensive, time consuming and risky proposition. As an alternative, we can take recourse to digital robotic simulation software tools which allow us to create a digital twin of the robotic work-cells. Robotic simulation software provides the ability to create, program and simulate a robotic work-cell in 3-D, taking into consideration real-world requirements and constraints, without the need and expense of setting up a physical prototype work-cell. This allows simulating the exact workings of a proposed automation solution, providing insights into the performance of a work cell, enabling fast iterations and saving time.

A. SIMULATION TOOL

There are a variety of robotic simulation tools available such as RobotStudio from ABB, DELMIA from Dassault Systemes, Tecnomatix from Siemens and ROBOGUIDE from FANUC. Since all the robots we use in this study are FANUC robots, we used FANUC's proprietary simulation software, ROBOGUIDE. With virtual robots and work-cell models, as well as offline programming, ROBOGUIDE reduces risk for manufacturers by enabling visualization of single and multi-robot work-cell layouts before a physical installation.

ROBOGUIDE allows the design and generation of three dimensional models of manufacturing work cells using included libraries with built-in models of all FANUC Robots, generic models of robot end-of-arm tooling (eg: vacumn gripper, mechanical gripper etc.), and, generic models of non-robotic components (e.g. conveyors, tables, platforms, fences). Components that are not available within ROBOGUIDE can be imported from external CAD environments. For instance in our example work cell setup in Fig. 44, the cells and cell holding templates have been designed in SOLIDWORKS and imported into ROBOGUIDE. This work cell also uses in-built components such as robot controllers, IR vision cameras, conveyors and safety enclosures.

A key component that is simulated in ROBOGUIDE is the robot controller. The robot controller is the computer that serves as the brain that controls the robot. It is important to note that when a robot controller is included in a ROBOGUIDE work cell, an exact replica of the controller software that controls an actual robot is loaded (Fig. 45). The fact that the simulation software is run on an emulation of the real robot controller allows for near identical duplication of the motion performance between the virtual and the real robot.

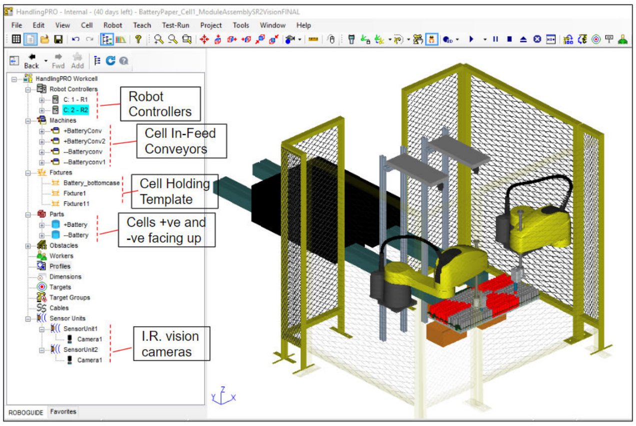

FIGURE 44. Work cell setup structure in ROBOGUIDE simulation software.

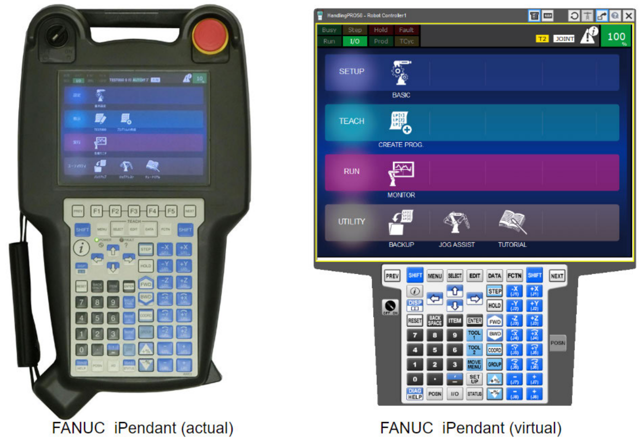

FIGURE 46. Physical teach pendant and virtual teach pendant.

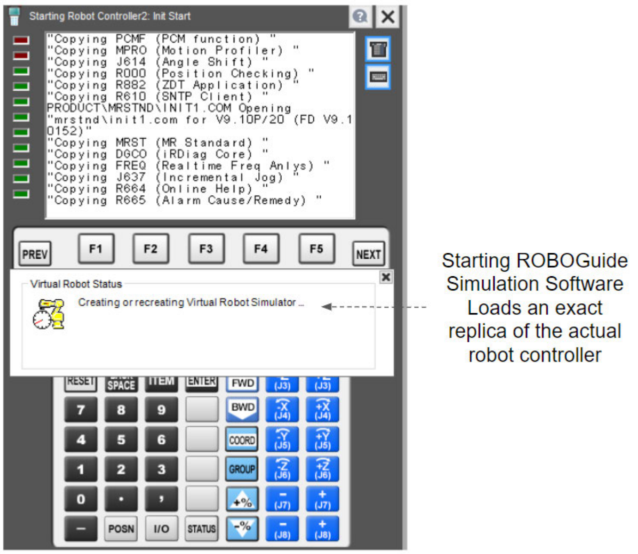

FIGURE 45. Virtual robot controller software.

FIGURE 47. Off-Line robot programming environment menu.

Further, several robots working in co-ordination, each under the control of a separate robot controller may be simulated within a work-cell.

Like most other robotic simulation software, ROBOGUIDE also provides an offline robot programming environment. The interface used to program the simulation is a virtual replica of the same teach pendant that would be used on an actual robot. An actual teach pendant and its virtual emulation in ROBOGUIDE is illustrated in Fig. 46.

Off-line programming can be done using a drop down menu environment which is an exact replica of the physical teach pendant (Fig. 47). Additionally, for complex programming needs, a proprietary scripting language called Karel is also available (Fig. 48).

Apart from the robot controller, other components also replicate their real life properties. For instance, the motion of conveyors and the functioning of IR vision cameras replicates how they would operate in the real world. Fig. 49 illustrates an example of a quality check of a cell for physical damage by an IR vision camera. In the illustrated simulation, the cell passes the quality check. If the cell had a physical defect, the camera would flash a rejection and the cell would be rerouted into a reject bin.

Apart from simulating the behavior of the robot controller, ROBOGUIDE also simulates the mechanics and dynamics of the robot. The payload capacity of robots is respected and if it is exceeded then the software will simulate an error to reflect real life scenarios. The virtual programming environment also lets the user perform advanced analysis on the motion path via the 'Tool Center Point' (TCP) trace (Fig. 30). TCP trace can be used to verify clearance between robots and fixed components as well as show speed and acceleration of the robot's tool center point. During the simulation of the robot program any collision that occurs between any objects in the work-cell may be automatically reported. Cycle times can be calculated for the overall sequence of movements. Additionally, the virtual environment provides the ability to perform duty cycle analysis as well as gear life analysis, which can indicate the effect of the virtual programmed path's effect on the real motors and gears of the robot.

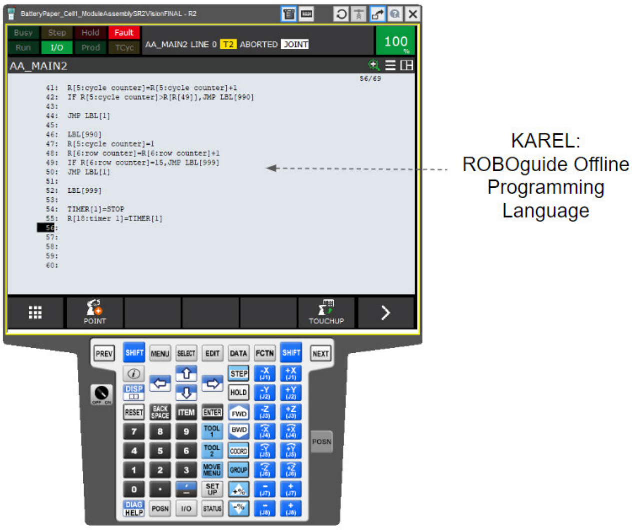

FIGURE 48. **KAREL: ROBOGUIDE Off-line robot programming language.**

FIGURE 49. **Off-Line simulation of iRVision camera functionality in ROBOGUIDE.**

B. SIMULATION METHOD

For the simulation phase, we used the work cell designs developed during the design phase in sections X - XIV as our starting point. In addition we also reference the sequence of operations and the process requirements for each operation as our starting point. A flowchart specifying the simulation process is presented in Fig. 50. The first step was to create a virtual robot world in the ROBOGUIDE simulation software. We then imported from ROBOGUIDE libraries, in-built models of the FANUC robots. The models of the robot mechanical units emulate the exact dynamics of a robot system which ensures that all movements are feasible and realistic. We also import from ROBOGUIDE libraries, generic models of robot end-of-arm tooling(EoAT) such as vacuum and mechanical grippers, standard components such as vision cameras, conveyors, stands, robot overhead structures, safety enclosures, and other components as needed in the work-cell. We also used SOLIDWORKS CAD software to developed 3D models of non-standard components such as work pieces, end-of-arm tools, and other cell components required in building the work cell. These 3D models were then imported into ROBOGUIDE.

These Robot models and 3D models of components were then used to construct layouts for each work-cell in ROBOGUIDE. The robots were then taught positions and motion paths. Finally, the robots were programmed using the Robot controller emulator contained within ROBOGUIDE. The robot virtual controller was programmed to meet the needs of each work-cell as described in sections X - XIV. Non-robotic aspects of the work-cell, such as conveyors, parts attaching to end-of-arm-tool when picked and detaching when dropped, were programmed and animated to interact with the robot, to visually convey the full operation of the cell. When necessary, motion of the robot was tuned to avoid interference with other robots, EoAT, carried work pieces and fixtures in the work cell. Additionally, robot location within the work cell, as well as robot motion speeds, were tuned to depict a realistic cycle that takes into consideration sustainable motor performance and longevity of the robot's gears over long term operation. Gripper actuation times, dispensing times, and screw driving times were estimated based on consultations with application-specific experts who have on average two to three decades of experience designing robotic work cells.

After the work cell layout has been detailed out in ROBOGUIDE, we run the simulation. ROBOGUIDE emulates the mechanical behavior of the robot and components. In addition, it also emulates the behavior of the robot controller and program as it will play out in the real world. Robotic simulation software have now advanced to even emulate the movement of flexible components such as cables and wires which was not possible earlier. This level of emulation of the real-world results in reproduction of actual robot kinematics and motion performance, including, motion speed, motor duty, and gear life estimation of the robot at specified payloads. Additionally, because the simulation is a digital twin, it limits the robot to its realistic work envelop. This is important as most robots have dead zones which they cannot reach.

Running the simulation allows us to detect collisions between robots and other objects, spot areas that are beyond the reach of the robot, simulate the payload capacity of the robot, simulate the execution of the software within the robot, simulate the dynamics of the robot, simulate the coordination of multiple robots within a work cell and evaluate and optimize time taken for a sequence of movements. We continue to iterate and refine the work cell layout and robot program to optimize the work cell for cycle time, robot duty cycle, robot gear life and power consumption.

Once satisfied with the robotic work cell operation, we finalized the design of the work-cells. These finalized work cell designs were then run in the simulation software in a mode which collects cycle time data of the robots.

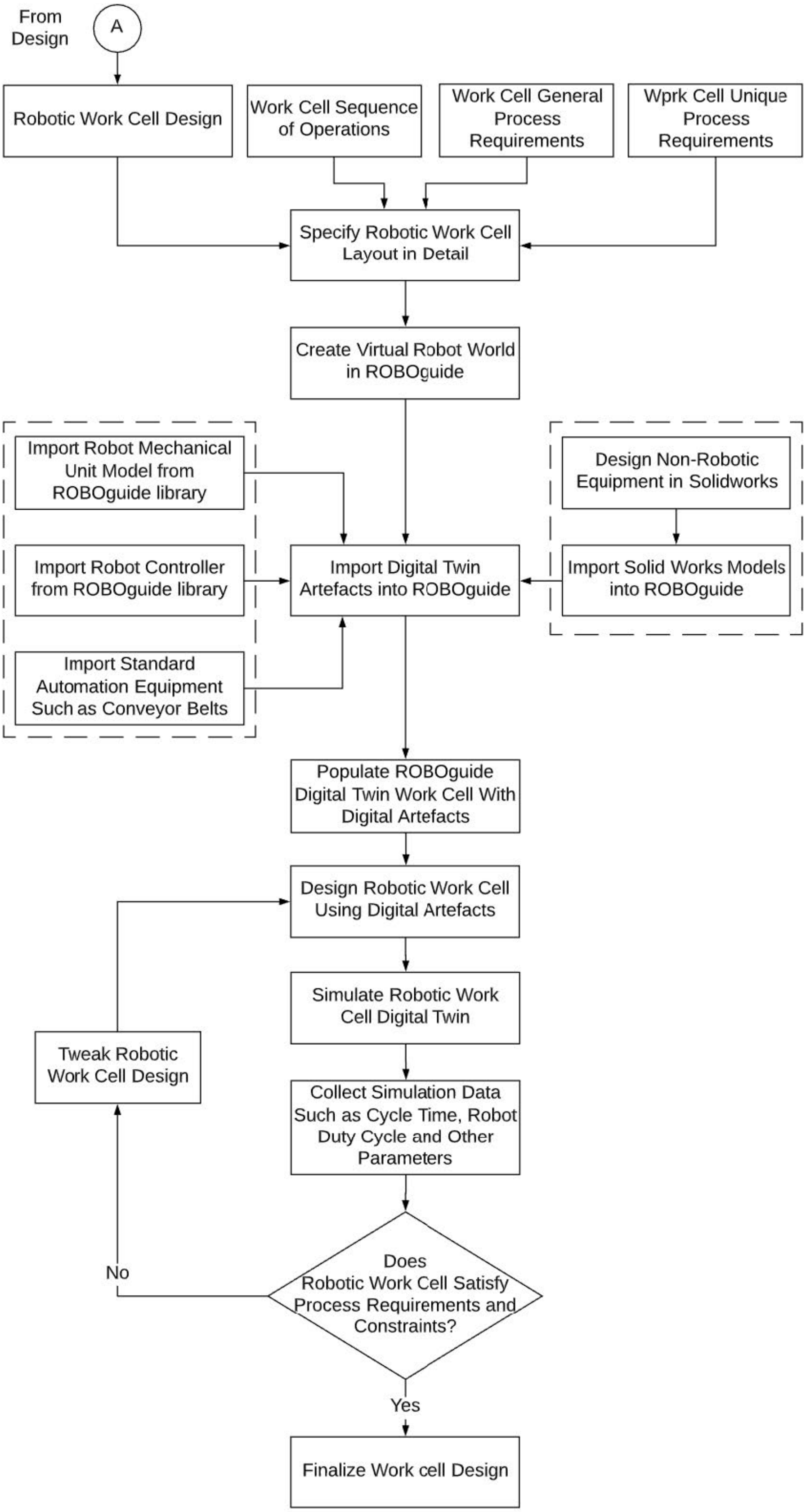

FIGURE 50. **Robotic work cell simulation process.**

TABLE 26. Robot cycle times.

Work Cell	Operation	Robot Model	Cycle Time(s)
Cell-Assembly			
Using Delta Robots	Cell Stacking	M-2iA/3SL Delta (+ve up)	154.45
	Cell Stacking	M-2iA/3SL Delta (-ve up)	147.3
Using SCARA Robots	Cell Stacking	SR-6iA SCARA	258.1
	Cell Stacking	SR-6iA SCARA	263.01
Dispensing			
	Adhesive Dispensing	LR Mate 200iD/7L	91.34
Wire Bonding			
	Wire Bonding	M-710iC/50	119.02
Manual Assembly			
	Manual Assembly		180
Final Closeout			
	Cover Placement	LR Mate 200iD	4.89
	Cover Screwing	LR Mate 200iD/7L	43.7

Since these simulated work-cells are digital twins of their physical counterparts, the generated cycle times represent what would be achieved by setting up and running an actual physical work-cell.The cycle time data collected from the simulation software is presented for each robot in Table 26.

XVI. LIMITATIONS AND FUTURE WORK

EV battery manufacturing process is a closely guarded secret by most OEMs and battery manufacturing firms. Thus, in order to arrive at the battery manufacturing process, we extensively researched publicly available information sources such as academic and industry publications, patents in the public domain, battery tear down videos, company news releases and letters to shareholders. Without direct observation of the production process, our rendering is likely to have some deviations from the actual process on the shop floor. However, our research has been extensive and captures the salient details necessary for designing a robotic solution. Additionally, we collaborated with a panel of industrial automation experts including electrical, mechanical, robotic and systems integration engineers. These experts each have over a decade of experience designing, simulating, implementing and supporting automation solutions for the automotive and other industries. This ensures that our proposed designs are realistic and validated for implementation in the real world.

A second limitation of our study is that we have designed, simulated and optimized individual work cells for each stage of battery module assembly. There remains a need to analyze and optimize the complete assembly line as a system to identify bottlenecks and dependencies that may exist between different work-cells.

A third limitation of our study is that its scope is limited to the assembly of the battery module. Battery modules are used to assemble the complete battery pack which is eventually integrated into the EV vehicle. Battery pack assembly involves putting together a large number of components using manual steps and hence may not be suitable for robotic automation. We are currently in the process of evaluating the assembly of the battery pack for possible automation.

Finally, for this research project we collaborated with one of the largest industrial automation firms. Because of this collaboration, all the proposed robotic work cells use robots from a single vendor. However, there are equivalent robot models available from other vendors which are equally likely candidates for each of these work cells.

XVII. CONCLUSION

It may not be an exaggeration to state that over the first 100 years of the automobile, its manufacturing process has been perfected into a science by the automotive firms. During this time, the DNA of the automobile has remained largely unchanged. Specifically, the automobile has been driven by mechanical energy provided by internal combustion engines running on fossil fuels. As a confluence of forces propels the automotive industry into an electric future, the automotive industry needs to evolve a highly efficient EV battery supply chain which can work in tandem with the rest of the automotive supply chain.

However, the automotive industry does not have experience assembling EV batteries and seems to be grappling with challenges in producing them in sufficient quantities. Some of the signs of this nascent stage of the EV battery supply chain is reflected in each automotive firm following its own unique battery pack design and the prevalence of manual steps in EV battery assembly. This lack of standardization and automation in EV battery assembly processes is likely due to a preoccupation with resolving the many challenges EV batteries have faced, such as, safety, low energy density, high cost and large size and weight. As battery technology transcends these limitations to become a viable alternative, we point to an urgent need to automate and standardize EV battery assembly into a reliable, flexible, efficient process yielding high quality EV batteries at scale.

In this paper, we have made an attempt in this direction. We carefully studied the battery module assembly process and find that it is highly amenable to automation with the exception of some manual assembly steps. We have designed and proposed robotic work cells for the entire EV battery module assembly process. These work cells have been simulated using digital simulation software to ensure readiness for real world implementation.

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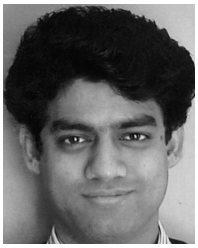

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