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ATOM Encoder Lights Out Manufacturing

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Declaration

I declare that this report, titled "ATOM Encoder Lights Out Manufacturing," is the result of my work and has not been submitted for any other degree or professional qualification. All sources of information have been duly acknowledged and referenced.

Acknowledgement

I would like to express my deepest gratitude to my supervisor, Rob Goodson, for his unwavering support, guidance, and invaluable insights throughout this project. His expertise and encouragement were crucial in shaping the direction and successful completion of this work.

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Abstract

This report investigates the automation of the ATOM encoder manufacturing process at Renishaw, a global engineering technology company. The project focuses on implementing lights-out manufacturing, which allows processes to run continuously with minimal human intervention, thereby enhancing efficiency and productivity.

Renishaw, established in 1973, specialises in precision measurement, motion control, additive manufacturing, and healthcare. Increasing demand for high-precision products has driven the company to adopt extensive automation processes. The ATOM encoder, a key product, is produced using automated and semi-automated systems within two segments: Index to Body and PCB to Body.

The literature review discusses the benefits and challenges of lights-out manufacturing. Key advantages include 24/7 operation, cost savings, and enhanced safety by minimising human exposure to hazards. However, challenges such as high initial costs and equipment reliability issues are noted. The review indicates that while lights-out manufacturing offers substantial benefits, its adoption is still evolving.

The methodology outlines the feasibility assessment steps, including data collection from Renishaw's systems, focusing on metrics like cycle time. Statistical analysis, including normality and goodness of fit tests, were conducted to understand data distribution and identify inefficiencies caused by human intervention.

Results indicated that human intervention in loading PCBs and unloading trays increased cycle times and production variability. Automating these tasks could lead to a more consistent and efficient process. The design and implementation section details the technical requirements and integration of mechanical and electrical components necessary for lights-out manufacturing. Technologies discussed include servo motor actuators, machine vision, and control systems, all aimed at achieving high precision and repeatability. Safety and compliance considerations were emphasized, ensuring all components met relevant standards.

The testing and validation phase involved running the new system through various scenarios to ensure performance. Validation confirmed that the lights-out solution met the desired outcomes, achieving a 98% yield. Post-implementation data analysis showed reduced cycle time variability and eliminated outliers caused by human intervention.

In conclusion, the study demonstrates that lights-out manufacturing for ATOM encoder production is feasible and beneficial. Key advantages include improved efficiency, reduced labour costs, and increased manufacturing consistency. The project supports Renishaw's strategy toward more automated systems, highlighting potential advancements in the manufacturing process. This study provides valuable insights into the benefits and practical considerations of implementing lights-out manufacturing, serving as a guide for future technological transformations in the industry.

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1 Introduction

1.1 Automation

Over the past 50 years, manufacturing process automation has become extremely prominent throughout a variety of industries. This has enabled organisations to maximise efficiency, increase productivity and revolutionise industrial processes. "Automation has become a key component in modern manufacturing systems, enhancing productivity, consistency, and safety, while reducing costs and human intervention" (Groover, 2019). Nowadays, when it comes to introducing a process to manufacture a product, an automated system will be at the forefront of system concepts. Whether this be a semi-automated system which requires human intervention, or a fully automated solution, automation can be present in various forms.

1.2 Renishaw

Renishaw is a global engineering technology organisation that specialises in multiple fields including precision measurement, motion control, additive manufacturing, and healthcare. Many of the products produced by Renishaw help customers transform manufacturing processes and innovate precision engineering operations. Established in 1973, Renishaw has been a global innovator for the last half-century. With R&D and manufacturing facilities based in the UK, this is where most of Renishaw's ventures take place. Even though this is the case, the organisation currently employs over 5000 people worldwide with locations in 36 countries.

As mentioned, Renishaw's key manufacturing operations take place in the UK. With major sites in Miskin (South Wales), Woodchester (Gloucestershire, England) and Stonehouse (Gloucestershire, England). One of the greatest sources of revenue is the position and motion control product line. These products can be split into three main categories which include laser encoders, magnetic encoders, and optical encoders. All of which are produced across the UK manufacturing sites. Due to the high precision nature of these products, the manufacturing process can be highly complex and present a range of different challenges for engineers.

Increasing customer demand over the years has forced the adoption of automation processes throughout the business. This is especially the case for the latest products, which are being designed with automation manufacturing processes in mind. As legacy products become discontinued, customers begin to purchase the newer products. One of the consequences of this is further increased demands, generating the need for greater manufacturing capacity.

Renishaw's journey towards automation reflects broader industry trends and underscores the company's commitment to staying at the forefront of technological innovation. The company's strategic focus on automation is not just about increasing productivity but also redefining what is possible in precision engineering. By continuously investing in research and development, Renishaw aims to push the boundaries of manufacturing capabilities and set new standards for the industry.

Responsible for making process developments and introducing innovative manufacturing processes at Renishaw are the Assembly Systems Group (ASG). The skillset of ASG personnel varies from mechanical bias to control system specialists. This is due to the nature of the projects undertaken by the department. With the company's manufacturing strategy moving towards automated systems, the technologies implemented by ASG are constantly evolving. Adopting this philosophy is essential to making technological advances when it comes to manufacturing. "The first rule of any technology used in a business is that automation applied to an efficient operation will magnify the efficiency."

1.3 ATOM Manufacturing

At the forefront of Renishaw's innovations is the ATOM encoder. This optical encoder delivered in a miniature package gives customers high repeatability and stability throughout their position control applications. Throughout the ATOM manufacturing process, automation is utilised to achieve a high-quality product while minimising production costs. Another objective of using automation in this manufacturing process is to maximise production capabilities. Fully optimising manufacturing operations and extracting the full potential of process automation is key to creating a productive environment.



Figure 1 - ATOM Encoder

The product is manufactured via a range of automated and semi-automated systems with one of the initial stages of the process being coring. During this stage, the core components of the unit are assembled utilising robotics. This presents a variety of challenges, one of which is the feeding of materials into the system. Operators are required to load materials into the system for the product to be assembled. As a result, production is limited to an extent, being dependant on shift patterns.

To improve production output, further developments to the system are required. Automation concepts, such as lights out manufacturing, could potentially be implemented which would help address the issues with material supply to the automated system. This report will investigate the advances in lights-out manufacturing within the industry and outline the implementation of a solution which utilises the concept. At the forefront of automated systems at Renishaw is the ATOM Coring Cell. This is a robotics system split into two segments, Index to Body and PCB to Body. The cells are connected via a belt conveyor which transfers trays of parts between the two platforms. See Figure 2 for reference.



Figure 2 - ATOM Coring Manufacturing System

1.3.1 Index to Body

The first stage of the ATOM coring process is called “Index to Body”. During this step, the shroud and index are applied to the encoder body. Bodies and shrouds are supplied to the system utilising bowl feeder technology. Parts are loaded into the appropriate bowl feeder, where they are filtered and orientated correctly via multiple intricate features. They are then passed onto separate belt conveyors and transferred to the final load position. An image of the bowl feeder is shown at Figure 3.

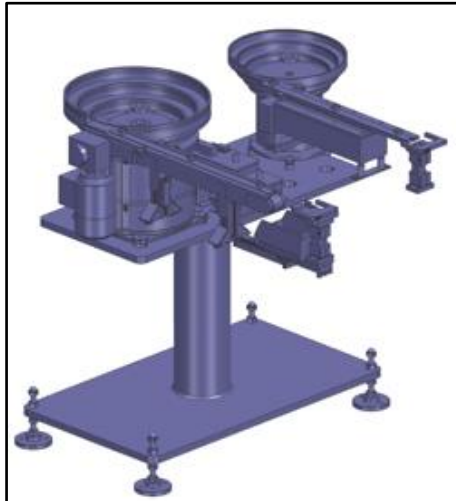


Figure 3 - ATOM Bowl Feeder

Upon reaching the final load position, the 6-axis robotic arm will transfer the unit around each assembly station in the following order: 1. Shroud Press, 2. Index Placement, 3. Adhesive Dispense and 4. UV Curing. Once a unit is complete, it is loaded into a bespoke storage tray, which accommodates 50 units. Complete units are shown in Figure 4 and Figure 5.

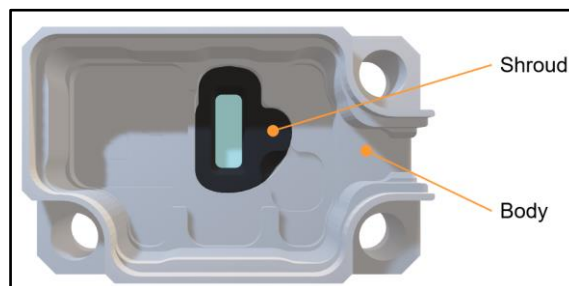


Figure 4 - ATOM Shroud to Body

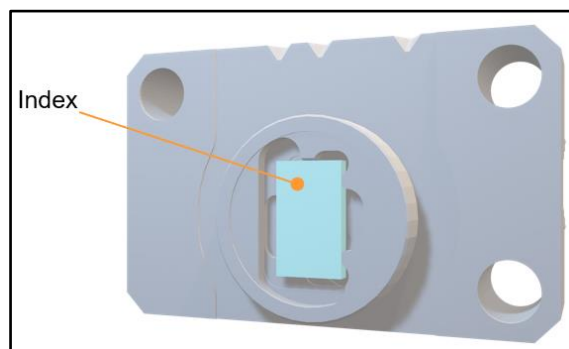


Figure 5 - ATOM Index to Body

1.3.2 PCB to Body

Following a tray of indexed units being fed into the “PCB to Body” platform, a similar process as described at 1.3.1 takes place and the 6-axis robotic arm will transfer the unit around the stations within the cell. The stations include PCB Routing, Adhesive Dispense, UV Curing and Auto Alignment Jig (AAJ). Unlike the previous process, PCB panels are loaded by the machine operator. Each panel holds a quantity of twenty-four PCBs. Once a panel has been loaded, each PCB is cut out and bonded into the Body with adhesive. The PCB requires alignment with the Index, which is where AAJ, shown in Figure 6, is employed.

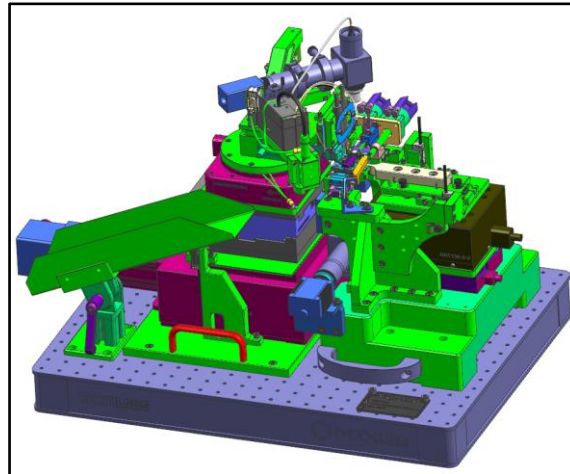


Figure 6 - ATOM Auto Alignment Jig (AAJ)

AAJ utilises multiple axes of high-precision motion to align the PCB with the Index, depending on the signal intensity output during the process. Once successful alignment is achieved, the adhesive will be cured with UV light. The finished unit, shown in Figure 7, will be loaded back into the fifty nest storage tray before being passed out of the machine.

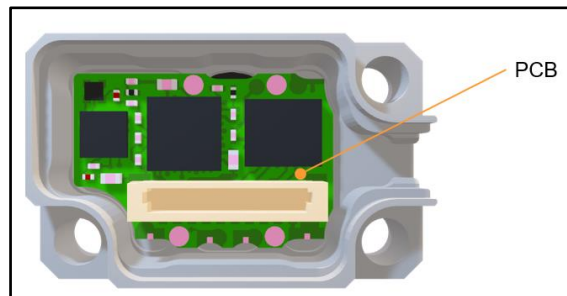


Figure 7 - ATOM PCB to Body

Limitations of the current process are associated with the loading of PCBs and the unloading of trays. Both operations are heavily reliant on operator intervention, which restricts the output of the system depending on the time it takes for the operator to intervene. Implementing a solution that would perform these tasks could be highly beneficial to the efficiency of the system. Investigating the concept of lights-out manufacturing further will assist in identifying an appropriate solution to the problem.

2 Literature Review

The automation of manufacturing processes has led to the development of a variety of concepts to optimise production efficiency. One of these concepts is 'Lights-out Manufacturing'. This enables a process to run 24/7 with minimal operator intervention, which is especially useful overnight when personnel may not be on site. There are a variety of academic sources that analyse this concept in depth and highlight the pros and cons associated with solutions that employ lights-out manufacturing.

"A well-known benefit of lights-out technology is the ability to manufacture at night" (Lee, 2018). This source, from the Missouri University of Science and Technology, investigates the use of lights-out technology by manufacturers in the future. The paper cites other benefits including potential cost savings and improved safety for operators in volatile environments. Also discussed are disadvantages of lights-out manufacturing including the initial implementation of such solutions and equipment reliability. Subsequently, the paper concludes the concept of lights-out manufacturing may not become widely utilised in the near future.

(Bapat, et al., 2022) presents the manufacturing developments made in response to the global Covid-19 pandemic. This also touches upon the concept of lights-out manufacturing. Particularly, the benefits associated with various types of production. These include additive manufacturing and injection moulding. One of the main advantages of lights-out manufacturing during the pandemic was the reduction of human intervention during production processes. In some cases, lights-out manufacturing eliminated the need for personnel to be present on-site. Also cited within this paper are the cost reduction and efficiency improvement benefits related to introducing such a system. Overall, this source highlights how advantageous lights-out manufacturing can be in terms of production flexibility.

It is essential to explore a variety of industries where the concept of lights-out manufacturing is utilised. (Jihao, Ellis, Tulpan, & Malpas, 2024) discusses manufacturing techniques employed in the production of poultry feed. Identified within this paper is the high degree of automation required to achieve lights-out manufacturing. As a result, a reduction in mistakes and variability due to human error is observed. Particularly, for poultry feed production, it is possible to unload the product into vehicles without requiring human intervention. This supports the previous point that lights-out manufacturing increases process efficiency. With the necessary means of automation, the possibilities for process improvements are limitless.

Presented in (Jia, Jebelli, Ma, & Ahmad, 2022) is the implementation of lights-out manufacturing to support the tending of autonomous machines. Described within this paper are systems appropriate to facilitate the introduction of lights-out manufacturing. Equipment described includes robotic systems that incorporate HMIs with emergency stop detection. Based on this information, the ATOM Coring Manufacturing Cell would be a prime candidate for upgrade as it already incorporates a variety of autonomous equipment, necessary for lights-out manufacturing.

To conclude, the literature review in this section has explored the concept of lights-out manufacturing thoroughly. This has helped to identify the pros and cons of the concept while supporting the fact that the philosophy could potentially be applied to the ATOM Coring Manufacturing Cell to assist with the issues identified with the loading and unloading of materials. Also, the advantages that could be obtained by reducing the need for human intervention within the process.

3 Methodology

Now that the philosophy of lights-out running has been explored within the Literature Review, the next stage is to understand whether it is feasible to implement a solution, that adopts this concept, to the ATOM Coring Manufacturing Cell. To justify the implementation, current production metrics need to be compared with the expected metrics after a solution has been installed. Currently, the common practice for Renishaw's in-house manufacturing systems is to record all production data for traceability purposes. Doing so also assists with identifying areas where a manufacturing process can be improved.

3.1 Data Collection

As mentioned above, production data can be interrogated due to the fact it is backed up to a server. "Effective data collection is critical in statistical control as it provides the necessary information to identify and understand process variations" (Montgomery, 2017). Utilising the SQL Server Management tool, a simple query can manipulate the data to return the required information.

```
SELECT [Record_ID]
      ,[Start_Time]
      ,[End_Time]
      ,[Cycle_Time]
      ,[Machine_ID]
      ,[Overall_Pass]
      ,[Failure_Mode]
FROM [Rig_Efficiency].[dbo].[Simple_Results]
WHERE Machine_ID = 'RUK29693' AND
Start_Time BETWEEN '2021-03-01 00:00:00' AND '2021-04-01 00:00:00'
```

Figure 8 - SQL Query

The query shown in Figure 8 returns multiple parameters from the 'Rig Efficiency' database, specifically the 'Simple Results' table. Stipulating the 'Machine ID' and 'Start Time' within the query returns a selection of results. An example of the format is shown in Table 1.

Record ID	Start Time	End Time	Cycle Time	Machine ID	Overall Pass	Failure Mode
631	2021-03-31 20:40:39.00	2021-03-31 20:41:50.00	153.0	RUK29693	0	AAJ Reject

Table 1 - Example Query Result

Selecting one month of production data returns a sample size of just over 500 records, which is a manageable quantity to apply statistical analysis tools. The metric which would support the implementation of a lights-out running solution is the 'Cycle Time'. This is recorded in seconds and is rounded to a whole number, which makes it a continuous data type. Conducting a normality test on the data would assist with identifying what kind of distribution the results conform to. Minitab is a statistical software package which can be used for data analysis and is what will be used to analyse the data set.

3.2 Data Analysis Process

"Statistical analysis is essential in technology and manufacturing, as it helps in understanding and controlling variability in processes, leading to more consistent and higher quality outcomes" (Chatfield, 2016). The first stage of the analysis is to conduct a normality test to determine whether the data follows a normal distribution, indicated by a bell curve. Completing the normality test is a critical stage in hypothesis testing. After performing the normality test, if the p-value is greater than the significance level, which is often set at 0.05, we reject the null hypothesis whereas if the p-value is less than the significance level, we reject the null hypothesis. Depending on the results of the normality test, the statistical analysis tools that can be applied during the analysis phase will vary.

3.3 Limitations

It is important to identify the limitations of the data collected before conducting analysis. One of the first limitations identified within the dataset is that cycle-time is rounded to the nearest whole number, before being recorded in the database. As a result, the analysis may not be statistically accurate and is subject to measurement error. Another limitation of the data available is the lack of traceability because serial numbers are not assigned until later in the manufacturing process. This makes it difficult to identify the exact cause for anomalies within the dataset.

Additionally, the sample size, limited to one month of production data, provides only a snapshot rather than a comprehensive view, potentially missing longer-term trends and seasonal variations. This lack of early-stage tracking impedes a detailed root cause analysis and affects the overall reliability of the data. Addressing these limitations in future research through more precise data collection methods, extended observation periods, and improved traceability systems would provide a more robust and insightful manufacturing process analysis.

4 Results & Analysis

Following the methodology outlined in section 3, the data obtained can be analysed utilising the statistical methods described. This involves performing a normality test on the data collected from the ATOM Coring Manufacturing Cell in March 2021.

4.1 Data Presentation

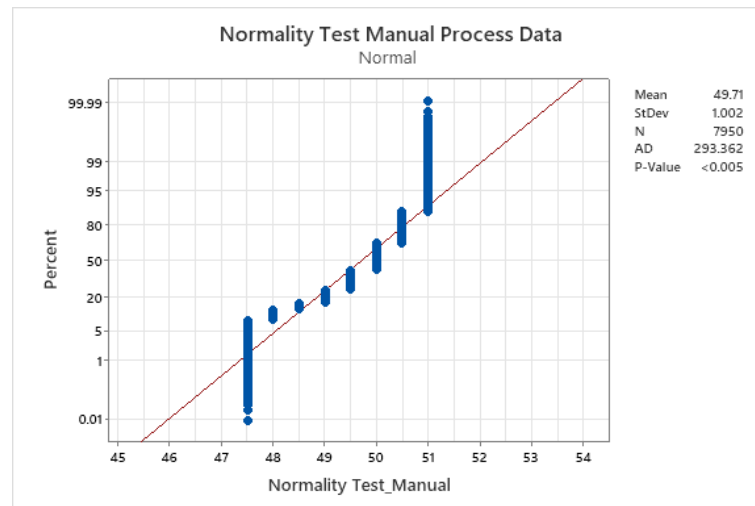


Figure 9 - Normality Test Process Data

"Normality tests are a crucial part of statistical analysis, as they help to determine whether data follows a normal distribution" (Ghasemi & Zahediasl, 2012). Based on the normality test performed on the data collected, shown in Figure 9, it can be determined that the results do not conform to a normal distribution. This is due to the extremely low p-value. Consequently, non-parametric tests that do not assume normality should be employed since they are equipped to deal with normality deviations. Performing a Goodness of Fit Test on the data, also supports the conclusion the data conforms to a non-normal distribution; therefore, we reject the null hypothesis. This is illustrated in Figure 10.

Goodness of Fit Test

Distribution	AD	P	LRT	P
Normal	293.362	<0.005		
Box-Cox Transformation	247.211	<0.005		
Lognormal	306.342	<0.005		
3-Parameter Lognormal	293.442	*	0.000	
Exponential	3509.782	<0.003		
2-Parameter Exponential	1427.286	<0.010	0.000	
Weibull	165.714	<0.010		
3-Parameter Weibull	162.164	<0.005	0.000	
Smallest Extreme Value	162.157	<0.010		
Largest Extreme Value	501.872	<0.010		
Gamma	301.983	<0.005		
3-Parameter Gamma	3080.680	*	0.000	
Logistic	240.052	<0.005		
Loglogistic	248.402	<0.005		
3-Parameter Loglogistic	240.069	*	0.000	

Figure 10 - Goodness of Fit Test

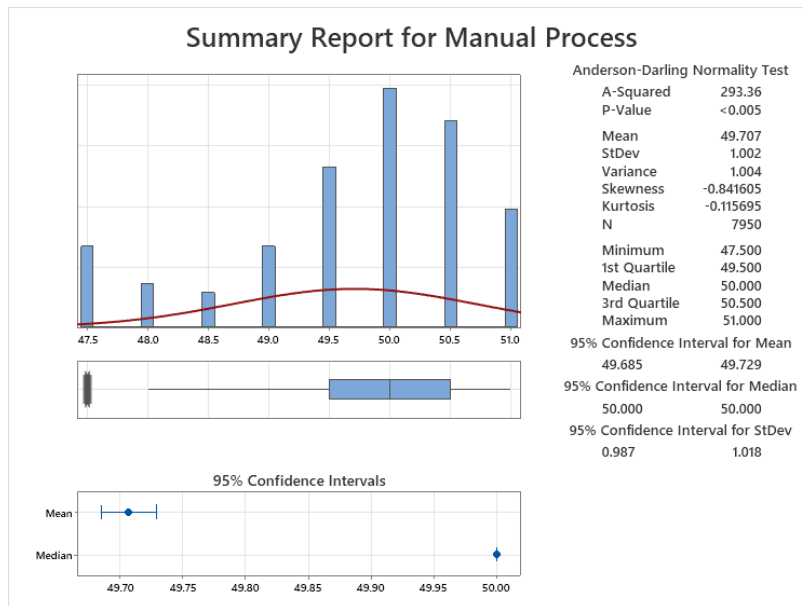


Figure 11 - Analysis Summary (Anderson-Darling Normality Test)

Figure 11 summarises the analysis performed utilising the Anderson-Darling Normality Test. The histogram displayed in the analysis shows a skewed distribution, hence the p-value being non-normal. A more prominent bell curve would suggest a normal distribution however, this is not the case. There are multiple factors which potentially cause the distribution to be skewed, ultimately this is caused by the increased cycle time for many of the units manufactured.

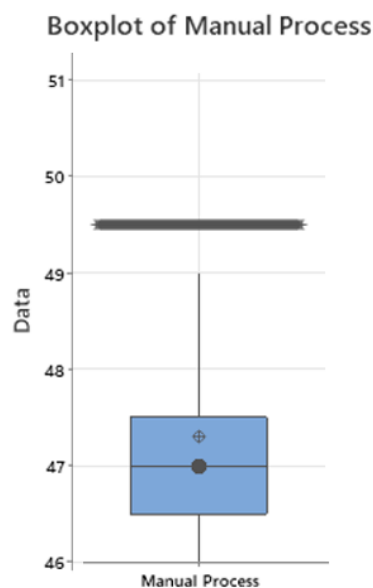


Figure 12 - Box & Whisker Plot

The Box and Whisker Plot, shown in Figure 12, assists with visualising the data range. This includes a median line, in the middle of the distribution, which represents the average cycle time. Also shown in the plot are outliers on the upper end of the distribution. These are caused by increased cycle times for several of the units manufactured during the period selected.

4.2 Discussion

Comprehending the data presented in the previous section requires an understanding of the factors that could be responsible for the distribution being non-normal. Overall, the most probable cause for the skewed distribution and notable outliers are the activities within the assembly processes that require human intervention. Delayed completion of these activities increases cycle time and decreases efficiency. With knowledge of the manufacturing process, it is possible to highlight the key areas where downtime is present.

One of the most likely causes of the outliers within the distribution is slow panel changes as this is the only stage in the process that requires human intervention. "Cycle time variability in manufacturing processes is often influenced by human intervention, which can lead to inconsistencies and inefficiencies" (Sanders & Sanders, 2018). Some operators may be more efficient when it comes to completing this process, which reduces the cycle time. Others however may take longer to complete the PCB panel change which in turn leads to an increased cycle time for certain units.

Other factors that may cause the cycle time distribution to be skewed include the system waiting for an operator to unload completed units from the machine. During this process, the operator will need to interact with the Human Machine Interface (HMI) before trays are released to the unloading dock. If this action is delayed, the system will be unable to process additional units until a free tray becomes available. The time it takes for the tray to be offloaded varies and is dependent on the skill of the human operator running the system at that time.

The difference in cycle times between units could also be explained by the deviation in time it takes for processes to complete. These processes include the adhesive bonding of the PCB along with PCB cutting and alignment. These are automated processes however, there may be a slight variation in the time it takes for these activities to be completed. It is, however, unlikely that these processes are the cause of the outliers displayed in Figure 12, due to the automated nature which would make the cycle time reasonably reliable.

4.3 Recommendations & Conclusion

After analysing data collected during the selected period, it suggests that implementing a solution to further automate the ATOM Coring Manufacturing Cell would be advantageous. The most significant benefit of implementing such a solution would be achieving a more consistent process. This is due to the likelihood of there being less variation in PCB panel loading and part tray unloading, because of removing the need for operator intervention at these points. Furthermore, it would also allow for an increased yield throughput from the system. Labour costs could also be decreased because of introducing a lights-out manufacturing solution to the existing process.

To conclude the analysis section, the data scrutinised has heavily implied that lights-out manufacturing could provide several improvements to the existing manufacturing process. More specifically the benefits associated with production efficiency and cost reduction associated with the current process. This also supports the initial hypothesis at the outset of this report, which implies lights-out running will solve issues with material supply to the system along with further advantages.

5 Design & Implementation

This section covers the design and implementation of a lights-out manufacturing solution to improve the ATOM Coring Manufacturing Cell. “Gradual implementation of Lean Six Sigma allows organisations to manage change effectively, ensuring each phase is integrated smoothly” (Sweeney, 2005). More specifically, this section of the report will investigate the industrial automation technology currently available to achieve the desired solution. The system will need to incorporate a high degree of repeatability which will in turn reduce production costs and increase the efficiency of the current process. By utilising technologies such as machine vision, servo motor actuators and control systems, a robust lights-out system could transform the current manufacturing process.

5.1 Planning

Before the design process can begin, a sufficiently detailed programme is required to achieve optimal implementation. One of the key factors in doing so is having a key project plan that outlines each phase of the project. A project management tool that is adopted across a range of sectors is a Gantt Chart. This outlines the start date and duration of each section of the project, along with the resource allocation requirements. It is important to assign sufficient resources to each phase of the project to ensure the project runs smoothly. The ability “to show a top-line perspective of a project. Gantt charts help workers and managers track tasks” (Ramos, 2021). See Appendix 2 – Project Plan section for a detailed view of the project plan shown in Figure 13.

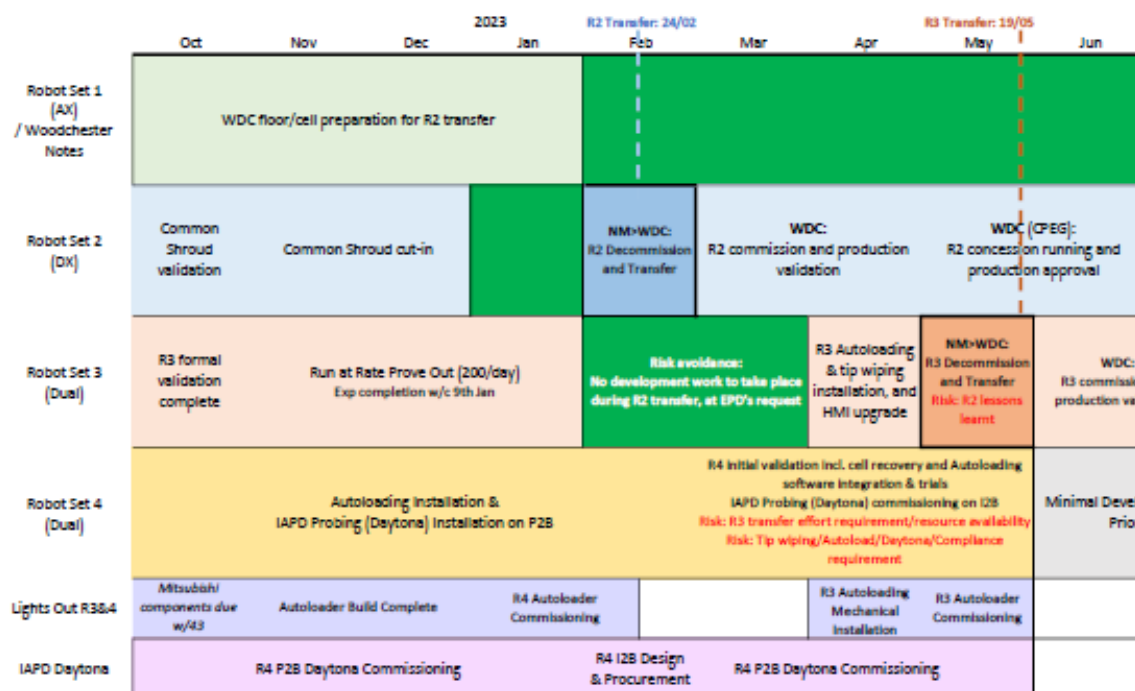


Figure 13 - Project Gantt Chart

Projects led by ASG at Renishaw adopt the Process Development Procedure (PDP), which is essentially guidance for engineers running a project. Following the strategy and plan being outlined, the next stage is to create a Requirements Specification. Included in the specification are the following aspects:

- Mechanical
- Electrical
- Software
- Production Metrics
- Validation & Testing
- Compliance
- Programming
- Maintenance
- Cost

For this project, the focus will be on the electrical, software, validation, compliance, programming, and cost factors associated with the implementation of the lights-out running solution.

5.2 Justification & Estimated Savings

Based on the conclusions drawn from the analysis section, a business case providing benefits, justification, and a breakdown of estimated savings can be produced. This will be presented to senior management for approval. Upon successful approval, a budget can be allocated to the project. For the project to receive approval, the proposal will need to include the estimated benefits which the solution will introduce.

5.2.1 Estimated Benefits

The budget is required to implement an automated PCB loading and tray unloading solution to the ATOM Coring Manufacturing System. Based on historical production data, the solution will provide the following benefits:

- Automatically load and unload parts into T-95176-05, removing the need for an operator to tend to the machine and replace a PCB panel every 48 minutes.
- During January 2020, 8,000 units were built with 6.5 hours lost due to slow panel changes by the operator. Only 5 units were built after 10pm. This upgrade will allow the machine to run continuously for an 8-hour shift without operator involvement.
- Predicted labour saving for slow panel changes is £3,500 per year based on the above 6.5hrs lost per month.
- Labour saving for a normal 2-minute operation would be £25.5 per day (double shift), this payback is based purely on the labour saving in a 12-month period.
- Unloading finished product is currently half the frequency of loading PCB panels and takes a similar amount of time. The solution aims to eliminate this operation from the process.
- The upgrade will load finished goods into a removeable magazine, which will be able to hold more than two shifts product. This removeable magazine could potentially hold 600 cores of a single variant type and can also be employed as a storage solution.
- With the added system functionality, a cassette of up to 12 panels would be loaded by an operator and the machine left to run until all panels consumed. This would approximately achieve up to 9.6 hours of running if fully loaded. The operator will then be alerted when the PCB cassette requires replacing.

5.2.2 Estimated Cost Breakdown

Item	Description	Quantity	Cost
Actuators	Distributed I/O, Electrical Actuators & Controllers	x1 of Each	£7,000
Machine Building Systems	Aluminium Extrusion Frame	x1 of Each	£550
Pneumatics	Pneumatic Components	x1 of Each	£350
Sensors	Various Sensors for System Control	x1 of Each	£1,100
Mechanical Tooling	Mechanical Tooling Manufactured In-House	x1 of Each	£1,000
Miscellaneous	Panels, Connectors & Miscellaneous Parts	x1 of Each	£900
Spares	Spares & Upgrade Materials	x1 of Each	£500
Total Cost			£11,400

Table 2 - Estimated Cost Breakdown

Following initial discussions with the project team, an estimated cost breakdown was drawn up. This will be used to inform the required capital expenditure budget for the project. Based on initial approximations, the capital budget for the project will be £11,400, as shown in Table 2. All the information presented in this section is summarised in the Project Charter, Section 5.2.3.

5.2.3 Project Charter: ATOM Encoder Lights Out Manufacturing	
Project Objective Summary: Develop an automated PCB loading and tray unloading solution for the ATOM Coring Manufacturing System. The improvements will allow for 8-hour lights-out running functionality.	Customer Product Division: EPD (Encoder Product Division)
	Project Team Members: Joseph McBride/Andrew Freeman – Control Systems Mark Sailes/Dorothy Scarborough – System Build James Baldwin/Harry Green – Mechanical Design
	Project Budget: Capital Expenditure - £12,000 Budget Approval: Gareth Hankins (Group Manufacturing Director)
Project Benefit Aims: - Automatically load and unload parts into T-95176-05, removing the need for an operator to tend to the machine and replace a PCB panel every 48 minutes. - Enable the system to run continuously for an 8-hour shift without operator involvement. - Achieve a predicted labour saving of £3,500 per year, based on the above 6.5hrs lost per month due to slow PCB panel changes. - Eliminate the need for the operator to unload completed parts at frequent intervals. - Introduce removeable magazine which could potentially hold 600 cores of a single variant type and can also be employed as a storage solution. - Implement functionality to permit approximately up to 9.6 hours of running if fully loaded.	Senior Management Team: Adrian Whitehead – Assembly Development Engineering Manager Nick Beauchamp – Assembly Systems Technical Manager Paul Richards – Technical Manager
Project Stakeholders: ASG (Assembly System Group), EPD (Encoder Product Division), Encoder Production Management.	

Table 3 - Project Charter

5.3 Process Description

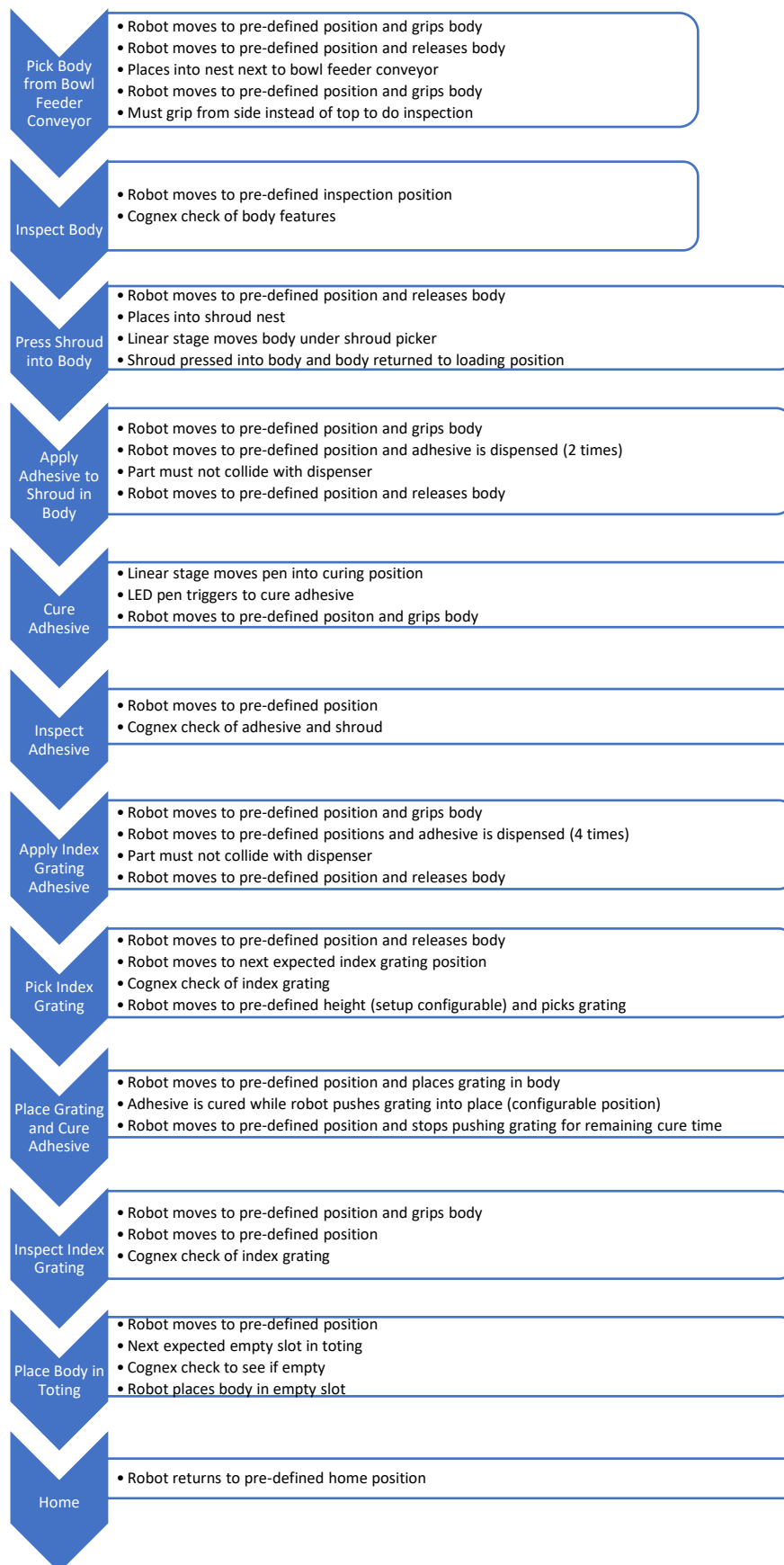


Figure 14 - Index to Body Process Description

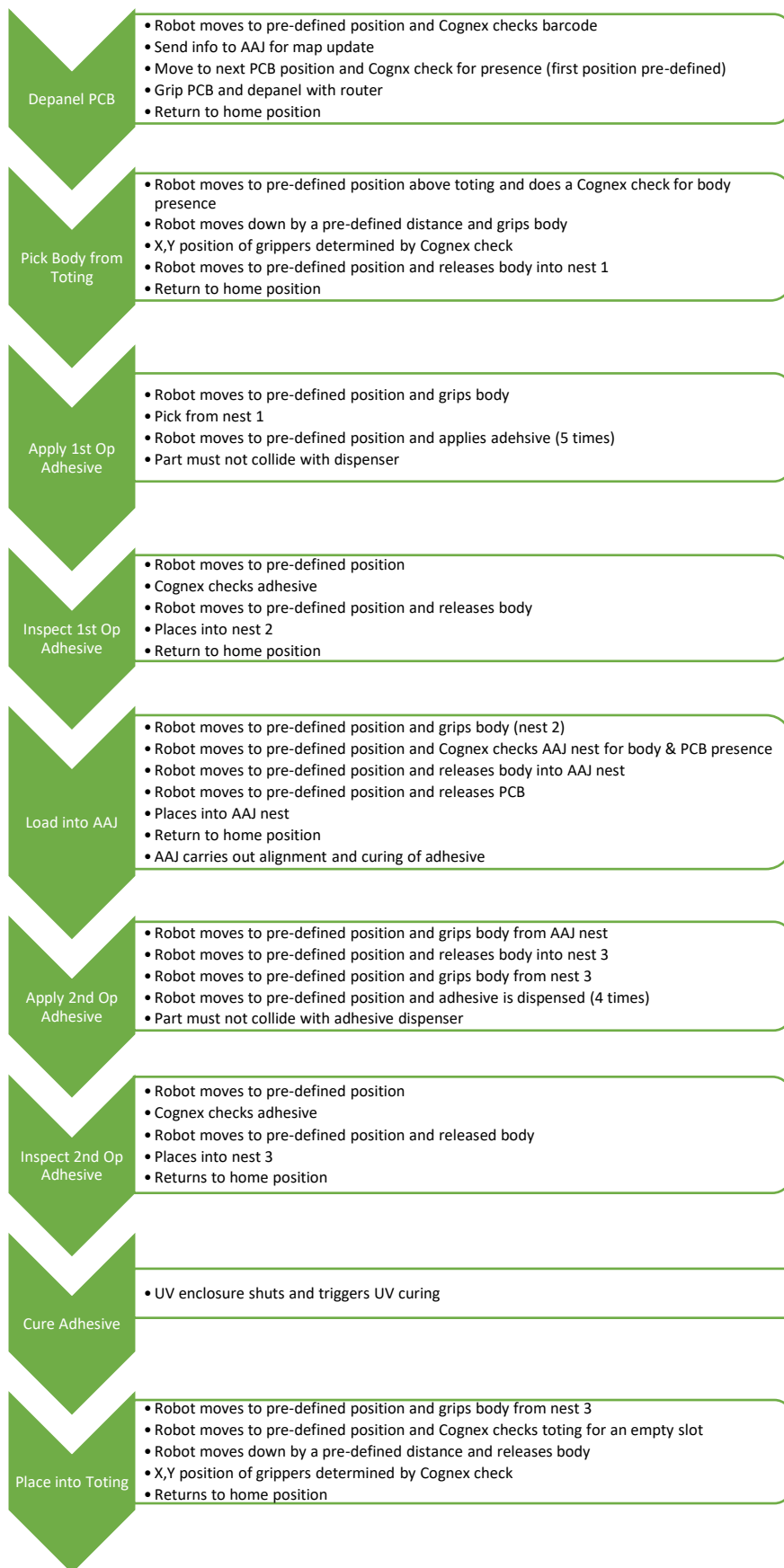


Figure 15 - PCB to Body Process Description

5.4 Requirements Specification

5.4.1 Introduction

The requirements for the lights-out running system to be introduced to the ATOM Coring Manufacturing Cell are detailed below. The system will utilise autonomous technology to load PCBs into the cell and unload trays of manufactured parts. All variants of ATOM PCBs, which include 20µm and 40µm options, will require loading into the machine. Minimal modifications should be made to the existing system so as not to compromise the integrity of the current production process.



Figure 16 - ATOM Tote Tray

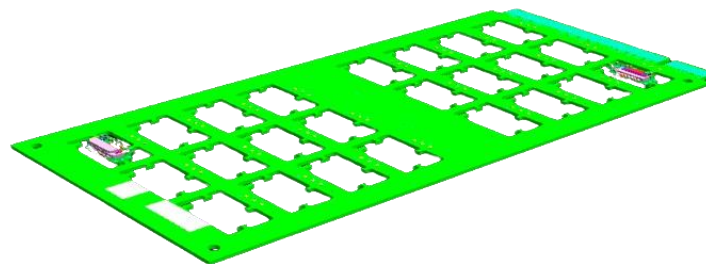


Figure 17 - ATOM PCB Panel

The lights-out solution should be capable of transferring the parts trays into existing storage mediums, that can be handled safely by operators. Changes to the dimensions of existing storage trays are not feasible and the system must be capable of robustly handling completed units, without causing damage. Tooling to enable the handling of parts can be developed inhouse by Renishaw, helping to maximise the project budget.

5.4.2 Machine Requirements

Ref	Requirements or Required Information
Mechanical	
1.1	Must be able to handle the current ATOM Tote Trays (300mm x 200mm x 7mm). Note that the tolerance on the tray thickness is ± 5mm. The current system utilises a belt conveyor to transfer the trays throughout the machine therefore mechanical tooling must be designed around this concept. A top-down view of a rectangular tray. The overall dimensions are 300mm in height and 250mm in width. The tray features a grid of 10 rows and 10 columns of circular holes. The grid is centered within the tray's frame. Figure 18 - Tray Dimensions (Top View) A side view of the tray showing its profile. The total height is 7.5mm. The main body of the tray is 6.5mm thick. The top edge of the tray has a slight lip or flange. Figure 19 - Tray Dimensions (Side View)
1.2	The system must be able to handle the ATOM PCB Panel (188mm x 86.7mm x 1mm). Bespoke tooling can be manufactured in house to achieve required tolerances. A top-down view of a rectangular PCB panel. The overall dimensions are 188mm in height and 86.7mm in width. The panel contains a grid of 10 rows and 10 columns of circular holes. The grid is centered within the panel's frame. Figure 20 - PCB Panel Dimensions (Top View) A side view of the PCB panel showing its profile. The panel is very thin, with a total thickness of 1mm. It has a flat top surface and a slight lip or flange on one side. Figure 21 - PCB Panel Dimensions (Side View)

1.3	Must be able to handle components with an accuracy of $\pm 0.25\text{mm}$. Renishaw products could potentially be used to accomplish this requirement.
1.4	Necessary for the tooling produced to load and unload materials in a batch format rather than individual units.
Electrical	
2.1	System must utilise components with 230V AC and 24V DC to comply with the current machine specification.
2.2	Must comply with the following electrical technical standard: <i>EN 60204-1:2018 Safety of Machinery – Electrical Equipment of Machines Part 1 General Requirements.</i>
Software	
3.1	PLC controlled application must be developed to align with the control system currently implemented. More specifically, software to be developed in Mitsubishi packages including GX Works 2 and GT Designer.
3.2	Part traceability required from system implemented (e.g. PCB barcode scanning and tray RFID reading). Jobs should be automatically processed with minimal human intervention required.
3.3	Ability to alter loading speed required to align with the current manufacturing process.
3.4	Ethernet IP or CC Link communication protocols to be utilised to comply with the requirements of the system at present.
3.5	Virtual engineering panel required for commissioning purposes. Access must be restricted to prevent unauthorised changes.
3.6	Performance monitoring metrics desirable but not essential.
Service & Maintenance	
4.1	Early life cycle equipment to be used to avoid issues with obsolescence in the event of a failure.
4.2	Ideally equipment implanted will arrive with an appropriate warranty however, this is not an essential requirement.
4.3	Components selected for the solution must have an infrequent maintenance and service period.
4.4	Solution should not require regular software and hardware updates.
Safety & Compliance	
5.1	Interlocking and E-stop functionality must be present to avoid operator encountering moving equipment or a dangerous situation. Also to comply with the following technical standards: <i>EN ISO 13849-1:2015 Safety of Machinery – Safety-Related Parts of Control Systems Part 1 General Principles</i> <i>EN ISO 12100:2010 Safety of Machinery – General Principles for Design Risk Assessment and Reduction</i>
5.2	Solution must conform to the Machinery Directive for CE and UKCA marked products. OEM procured equipment must also comply to these standards.

Table 4 - Machine Requirements

5.5 Technology Integration

Now that the machine requirements have been outlined, the technology required to achieve the desired solution can be specified and procured. The machine requirements can be split into two sections, these include the PCB loader and tray unloading aspects. “Mechanical and electrical integration is fundamental to the success of automated systems, ensuring seamless operation” (Morey, 2019).

5.5.1 Mechanical

Firstly, the focus will be on the mechanical solution for PCB loading. Based on the current process, outlined in the Process Description. The machine calls for the operator to load the PCB panel into the tray before the individual PCB can be cut out by the router. The technology delivering the lights-out option, will need to emulate this process. This could be achieved by implementing a gantry-type system, that picks the PCB panel from a fixed location and loads it into the tray ready for routing. Two directions of motion would allow the gantry to move in X and Z. (Horizontal and Vertical Movement). This is illustrated in Figure 22.

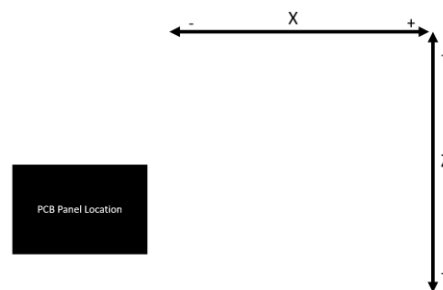


Figure 22 - PCB Loader Concept

Following a design review with the mechanical engineering team, the concept was agreed between all stakeholders. After providing the control system requirements, the lead mechanical engineer designed the solution shown in Figure 23. This solution incorporates two ball screw linear actuators, manufactured by Festo, that can be driven by a selection of servo motors. Based on the current system, the obvious choice was to select the MELSERVO-J4 Series supplied by Mitsubishi, due to the components already being utilised within the system and their compatibility with Festo actuators. Another reason the motors were selected was due to the high-accuracy positioning features and easy integration with Mitsubishi PLC software.

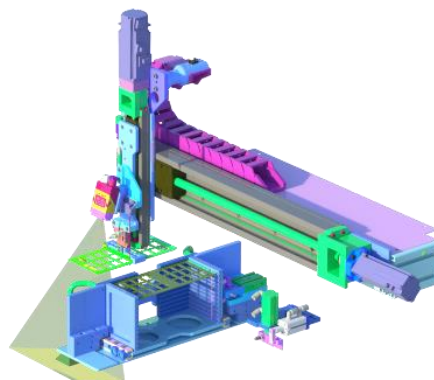


Figure 23 - PCB Loader CAD Model

The PCB loading solution incorporates a cassette, that accommodates 12 PCB panels. Each panel contains 24 individual PCBs, meaning a total of 288 units can be manufactured based on the capacity of one cassette. Figure 244 illustrates the cassette design, which includes a pneumatically actuated spring-loaded latch. The purpose of the latch is to ensure that the PCBs are all positioned correctly. An operator will be required to manually insert the panels into the cassette, before loading it into the machine. The quantity of PCBs in the cassette allows the machine to run overnight, unattended and will only require attention when personnel are on site the following morning. This also fulfils the requirement for batch-loading materials into the system. The tooling designed and manufactured by the mechanical design division satisfies the dimensional requirements of the machine specification.

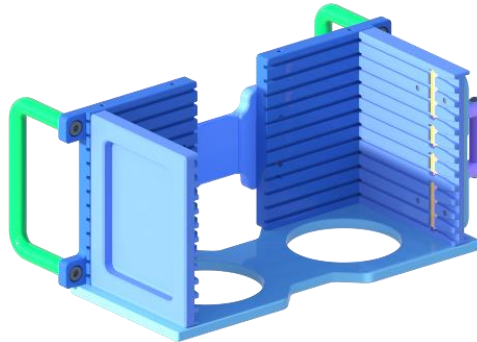


Figure 24 - PCB Cassette

Now that the mechanical solution for PCB loading has been discussed, the tray unloading aspect of the system can be covered. After considering similar techniques for system unloading, a concept like the one shown in Figure 24 was developed by the mechanical design engineering division. This concept incorporates a single axis of motion in Z (Vertical Movement) to position a tray magazine at the conveyor output. Completed parts trays will then be unloaded and stored in the tray magazine, to remove the need for operator intervention following the completion of each tray.

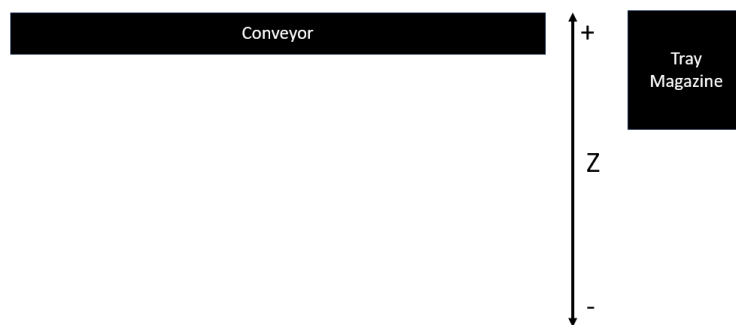


Figure 25 - Tray Unloading Concept

Based on the above concept the following solution, shown in Figure 25, was produced by the mechanical engineering team. The solution in question utilises similar components to the PCB loading system, including one linear actuator driven by a Mitsubishi servo motor. A tray magazine, which can hold 12 trays of completed parts (600 Units), is driven vertically to align each slot of the magazine with the end of the conveyor. Once the tray is detected in the unload position, a pneumatically actuated pusher will send the tray into the magazine. This removes the need for human intervention during the tray-unloading process.

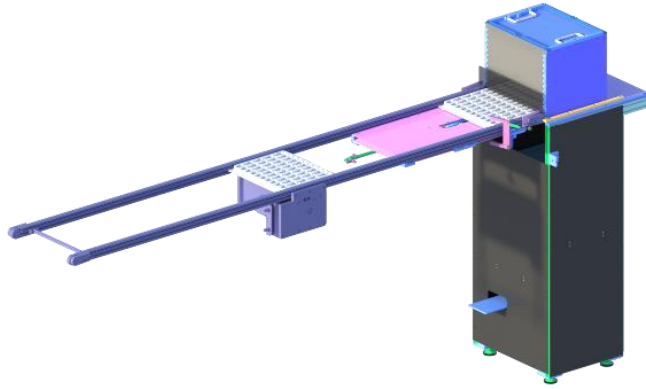


Figure 26 - Tray Unloader CAD Model

Once the magazine has reached capacity with completed parts trays, the machine operator will be alerted by a buzzer. The operator will be required to remove the full magazine and reload an empty magazine in its place. Like the PCB cassette, the quantity of the magazine enables the system to run lights-out with interaction only being required when personnel are present on site. All the tooling designed by the mechanical engineering division conforms with the requirements laid out in Table 4. For example, the solution incorporates the dimensional considerations in the mechanical section along with fulfilling the requirements for the various other sections by selecting the appropriate components from suppliers. Collaboration between divisions allowed for successful component selection to meet the requirements outlined.

Mechanical Component Breakdown (External Manufacturers)		
Manufacturer	Part Number	Description
Festo	EGSL-BS-55-250-5P	Tray Unloader Z Axis Actuator (250mm Travel)
	EGSK-26-150-6P	PCB Loader Y Axis Actuator (150mm Travel)
	EGSK-46-400-20P	PCB Loader X Axis Actuator (400mm Travel)
	EAMM-A-P5-28B-40R	PCB Loader Y Axis Actuator Axial Kit. Compatible with Mitsubishi Servo Motor.
	EAMM-U-60-D40-40R-91	Tray Unloader Z Axis Actuator Parallel Kit. Compatible with Mitsubishi Servo Motor.
SMC	JMHZ2-8D1	PCB Loader Pneumatically Actuated Parallel Gripper
	RSDQA16-15DZ	PCB Tray Stopper Pneumatic Cylinder
	MKB12-10RNZ	PCB Tray Pneumatic Rotary Clamp
	CD85N10-250C-B-X2018	Tray Unloader Pneumatic Pusher Cylinder

Table 5 - Mechanical Component Breakdown

Table 5 contains a breakdown of all externally sourced mechanical components utilised within the lights-out solution.

5.5.2 Electrical

The solution specified in the previous section incorporates several components from various suppliers which require installation into the current control system. All the components selected by the mechanical design engineers were reviewed with control engineers to ensure that they meet the requirements of the current system. A breakdown of components that require integration into the control system can be found in Table 6.

Electrical External Component Breakdown		
Manufacturer	Part Number	Description
Mitsubishi	MR-J4-20B-RJ	Mitsubishi Servo Amplifier Compatible with Selected Servo Motors. 230V AC Supply. CE Marked Component.
	HG-KR13B	Mitsubishi Servo Motor HG Series. 100W Power with 1.1Nm Maximum Torque. CE Marked Component.
	QD77MS4	Mitsubishi Q Series PLC Motion Control Module. Four Axis of Motion Capability.
Festo	50E-F24GCQST43ERERORLR-D 32P-SGL-R-MA-4G	Auto Loading Valve Manifold (Pneumatic Controller). 24V DC Supply with CC-Link Fieldbus Communication.
Cognex	DMR-260S-0110	Data Man 260S Fixed ID Reader. 24V DC with Ethernet IP Communication Capability.
Pilz	PNOZ Multi EF 4DI 4DO (772143)	PNOZ Multi Safety Relay. 4 Digital Inputs & Outputs with 24V DC Power Supply.

Table 6 - Electrical Component Breakdown

Based on the requirements specified to the supplier, the Mitsubishi MELSERVO MR-J4 Amplifier along with compatible HG Servo Motors was selected. These components are shown in Figure 27. The characteristics of the equipment, including the 230V AC power supply and output torque, make them suitable for the application. The components are CE marked; a key requirement of the machine specification and therefore makes them an appropriate choice for the lights-out solution. The MR-J4 series of amplifiers is used in the PCB Router assembly and allows for less complex software integration. Absolute encoder position feedback and the fact that the motor is braked - a feature required for the vertical axis of motion, are additional factors that contribute to the selection of these components.

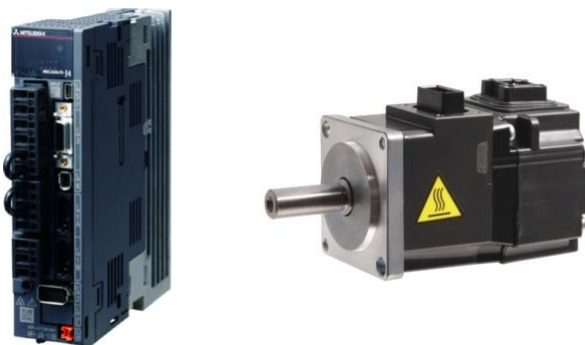


Figure 27 - Mitsubishi MR-J4 Amplifier & HG Servo Motor

For motion control capability, the Mitsubishi QD77MS4 Motion Control Module, shown in Figure 28, was selected. This module is compatible with the Q Series PLC and enables communication between the control system and servo drives. Integration is also made simple by selecting the control module from the same manufacturer as the drive components. The module permits four axis of motion control which makes it suitable for this application, as only three axes of movement are required. Communication between the module and servo drive is enabled through Mitsubishi's SSCNET protocol. This protocol requires the amplifiers to be connected to the module in series utilising fibre optic cables.



Figure 28 - Mitsubishi QD77MS4 Motion Control Module

Utilised throughout the lights-out solution are several pneumatically actuated components. These components will be controlled via the Festo Valve Manifold, shown in Figure 29. The manifold incorporates I/O (Input & Output) controlled pneumatic solenoid valves which can be communicated with over Mitsubishi's CC-Link communication protocol. This makes integration with the current control system unproblematic.

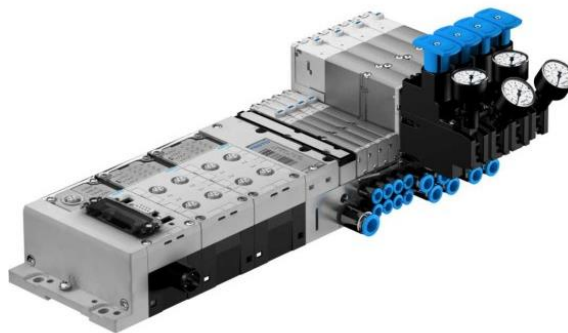


Figure 29 - Festo Pneumatic Valve Manifold

One of the aspects of the machine specification was part traceability, which led to the Data Man 260 from Cognex being selected. This component was chosen for multiple reasons. These include the 24V DC power supply, which makes it compatible with the current control system along with the Ethernet IP communication protocol functionality. Another reason this fixed ID reader was selected is other device variants are implemented across other in-house manufacturing systems and therefore assists with standardisation of equipment selection. The Data Man 260 also supports the SLMP industrial protocol, which enables seamless integration with Mitsubishi PLC software.



Figure 30 - Cognex Data Man 260 ID Reader

Other factors that contributed to equipment selection included the need for minimal maintenance interventions, limiting any additional maintenance burden on the organisation. Safety and compliance considerations required that all the equipment procured complies with CE marking requirements. Additional documentation which aided with equipment selection is located in Appendix 3 – Equipment Manuals. "Smart manufacturing technologies are essential for precision engineering, offering enhanced control and flexibility in production processes" (Garcia & Johnson, 2022). The components selected ensured that the precision of the process was not compromised.

Following the component selection for the lights-out solution, a wiring diagram was created which could be used by technicians during the installation stage of the project. A copy of the detailed wiring diagram is included at Appendix 4 – Wiring Diagram. A copy of the wiring diagram is necessary for compliance purposes and for future reference to aid fault finding in the event of equipment breakdown or component failure.

5.5.3 Functional Safety

Another key aspect when it comes to the design of the lights-out running solution is functional safety. One of the requirements of the machine specification is compliance with the EN ISO 13849-1:2015 Safety of Machinery standard. This standard applies to the safety evaluation of complex machinery. To fulfil the requirements of this technical standard, several criteria need to be met. The overall aim of the standard is to determine the performance level of a system through the safety-related components utilised. In this case, before the addition of the lights-out running solution, the system was already assessed and adhered to the criteria for PLe rated system. The categories are broken down in Figure 31.

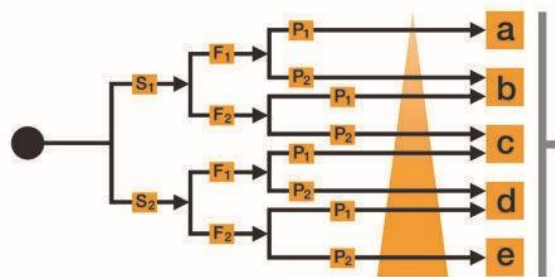


Figure 31 - Functional Safety Performance Level Breakdown

Outlined below is the process for assessing the performance level of a system, following the guidelines of the functional safety technical standards. This ultimately determines that the ATOM Coring Manufacturing cell requires PLe functional safety protection.

S – Severity of Injury

S1 = Slight (normally reversible injury)

S2 = Serious (normally irreversible injury or death)

F – Frequency and/or Exposure to Hazard

F1 = Seldom to less often and/or exposure time is short

F2 = Frequent to continuous and/or exposure time is long

P – Possibility of Avoiding Hazard or Limiting Harm

P1 = Possible under specific conditions

P2 = Scarcely possible

A PL e rated system corresponds to machinery with the highest possible risk rating. This means only components PL e rated can be used on the system. As a result, the Pilz PNOZ 4DI 4DO Safety Relay, illustrated in Figure 32, was selected. The four digital inputs and outputs respectively are sufficient for the lights-out running application. It is also compatible with the Pilz mB0 controller, which is the main control module for the functional safety system.



Figure 32 - Pilz PNOZ Multi 4DI 4DO Safety Relay

The Pilz PNOZ Multi 4DI 4DO Safety Relay also offers seamless integration through the PNOZ Multi Configurator software package, shown in Figure 33.

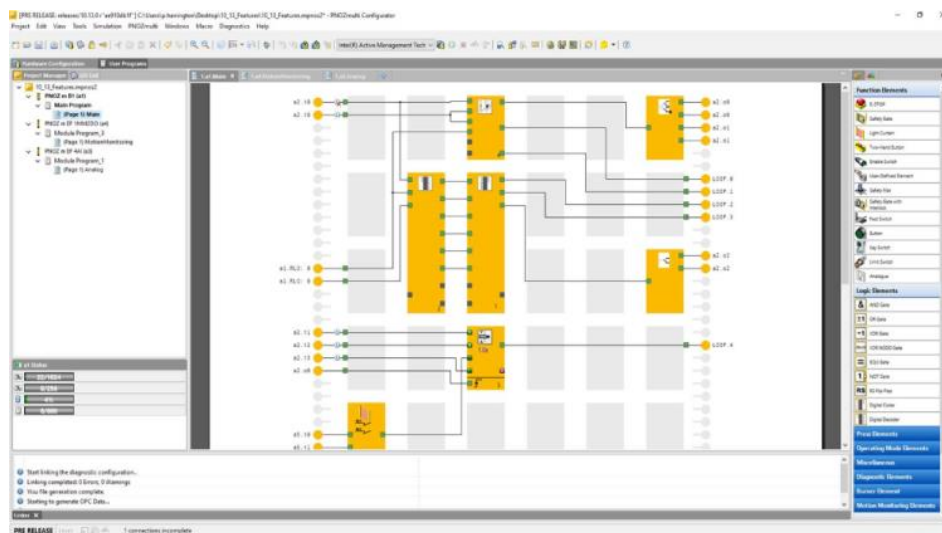


Figure 33 - Pilz PNOZ Configurator Package

5.5.4 Software

A key requirement of the machine specification is software alignment with the current control system. Fulfilling this requirement involves developing the PLC software within the Mitsubishi GX Works 2 development suite (Figure 34). Various PLC programming languages can be implemented including Ladder Logic, SFC (Sequential Function Charts), Structured Text and Function Block Diagrams. For this specific application, software will be developed in Ladder Logic and SFC respectively. The justification for this decision is that the programming languages are those already used adopted for the existing machine element's control system.

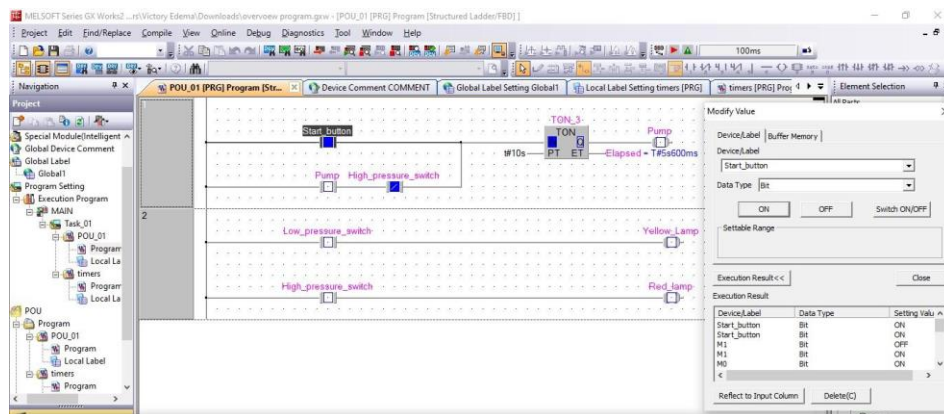


Figure 34 - Mitsubishi GX Works 2 Development Suite

HMI software development is fulfilled through the Mitsubishi GT Designer 3 development suite, shown in Figure 35. Additional HMI functionality is a requirement of the lights-out solution, which leads to the introduction of additional screens. Both the PLC code and HMI screens developed for the Auto Loading system can be found in Appendix 1 – Commissioning Guide section of the report.

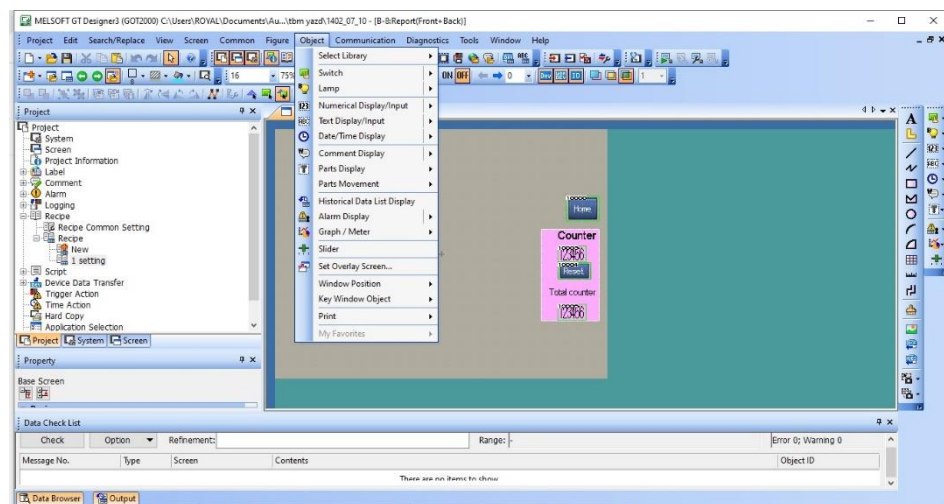


Figure 35 - GT Designer 3 Development Suite

5.6 Implementation Costs and Return on Investment (ROI)

This section of the report provides a financial breakdown of the costs associated with the implementation of the lights-out manufacturing solution. Also included in this section is an analysis of the financial benefits brought about by the introduction of the system.

5.6.1 Implementation Costs

Vendor	Description	Cost
Festo	CPX Manifold & Actuators	£4,500
Mitsubishi	Servo Motors & Controllers	£5,000
Machine Building Systems	Aluminium Extrusion Profile	£500
SMC	Pneumatic Components	£360
Baumer	Sensors	£250
Keyence	Sensors	£350
Miscellaneous	Machine Parts	£1000
Total Cost		£11,960

Table 7 - Implementation Cost Breakdown

5.6.2 Return on Investment (ROI)

Labour Saving

- Estimated labour saving of £3,500 by eliminating slow panel changes.
- £9,180 annual labour saving for a normal operation, based on a triple shift pattern.

Return on Investment

$$ROI = \frac{NET\ BENEFIT - INVESTMENT\ COST}{INVESTMENT\ COST} \times 100$$
$$ROI = \frac{£12,680 - £11,960}{£11,960} \times 100$$
$$ROI = 6.02\%$$

Project Payback

$$Payback = \frac{£11,960}{£6,708} = 1.78\ years$$

The implementation of the lights-out manufacturing solution involves an initial investment of £11,960. The projected annual labour savings amount to £9,180, leading to a return on investment (ROI) of 6.02%. The payback period for this investment is estimated to be 1.78 years. These financial metrics indicate that the implementation of the lights-out manufacturing solution is a viable and beneficial investment for the company, promising significant cost savings and a relatively quick payback period.

5.7 Risk Assessment

Following the implementation of the lights-out solution, a risk assessment requires completion to ensure no additional hazards have been created by the system. The risk assessment process involves assessing the potential risks involved with the equipment and confirming that they have been managed adequately so that no harm is caused when using the platform. Due to the equipment falling within the scope of the Provision and Use of Work Equipment Regulations (PUWER), it is a requirement that a risk assessment is performed before Renishaw personnel use the equipment. During a risk assessment, hazards are identified and scored based on the initial risk presented. Reduction and control actions are then applied, if applicable before the residual risk is scored. If the residual risk is rated between zero and six, it is deemed to be acceptable following all practicable risk reduction actions being taken. Any risk scored greater than six is deemed to be unacceptable and must be reduced. Below, in Table 9, is the specific risk assessment for the ATOM Coring Cell lights-out manufacturing system. Also, see below in Table 8, the key rating table which is used for calculating the risk score.

Severity		Likelihood		Rating Acceptability	
0	Temporary Pain with 0 Injury	0	Effectively 0 and Will Not Happen	0-5	Acceptable
1	Minor Injury with Minimal Time Lost	1	Never Expected to Happen	6	Acceptable if Risk Reduction is not Reasonably Practicable.
2	Injury with up to 3 Days Lost	2	Extremely Unlikely		
3	Reportable Injury with Over 3 Days Lost	3	Very Unlikely		
4	Major Injury with Long Term Absence	4	Unlikely		
5	Death	5	Multiple Occurrences Expected	7-10	Unacceptable

Table 8 - Severity, Likelihood and Rating Acceptability Calculator

No	Task/Hazard	Harm	Actions Already Completed Prior to Initial Assessment	Initial Risk			Completed Risk Elimination/Reduction/Control Actions	Residual Risk			Result
				S	L	R		S	L	R	
1	Mechanical										
1.1	Sliding PCB Panel Nest.	Crushing of Hands/Fingers.	Warning in Work Instruction (WI) and hazard sticker that warns the operator. Damper also installed that prevents crushing of full hand due to the gap and momentum is dampened. Mechanism is also low speed and power.	2	3	5	Hazard tape applied to panel and linear rails to emphasise hazard region. "Caution platform may move unexpectedly" and mandatory "keep hands clear" labels applied. Buzzer sounds implemented to indicate movement of carriage outside machine.	2	2	4	Pass
1.2	Protruding Tray Stacker.	Injury to Operator.	Black and yellow hazard taped applied to attract attention so injury can be avoided.	1	1	2	No additional action required.	1	1	2	Pass
1.3	Input from Conveyor Window Provides Access into the Machine.	Damage to Hands/Fingers.	'Letterbox' window width smaller than 20mm. Plate installed to protect limbs if inserted and extended over 120mm to comply with BS EN ISO 13857:2008.	1	1	2	No additional action required.	1	1	2	Pass
1.4	Entrapment of Fingers/Hands.	Damage to Hands/Fingers.	All parts have been designed to ensure fingers cannot be trapped in machined features.	2	1	3	No additional action required.	2	1	3	Pass
1.5	PCB Panel Clamp.	Pinching/Trapping of Hands.	Clamps are chamfered on the bottom face which makes it difficult to get fingers pinched underneath. Potential for hand to be pushed into parts on the PCB panel. Low clamping force and warning in WI. Also, warning sticker that warns the operator.	1	1	2	No additional action required.	1	1	2	Pass
1.6	Mains Air Supply Over Pressure.	Damage to System/Harm to Operator.	Localised pressure regulator and isolation located inside machine.	1	1	2	No additional action required.	1	1	2	Pass

			Internal pressure regulated to 5MPa. Unregulated air hose below head height. Hoses secured using cable ties and contained within enclosure which are not accessible.								
1.7	Automated Movement of Core Tray Stacker.	Injury to Operator in Form of Crushes or Collisions.	Mechanism is low speed. Black and yellow warning tape added to attract attention. Entrapment hazard labels attached to stationary and moving platforms.	3	2	5	Top 'lips' removed to prevent entrapment at extent of travel. Torque limit reduced to minimise risk of entrapment injury. Internal panels added to the stack lift to eliminate shear points. E-stop also relocated to reachable distance of the stack lift.	2	1	3	Pass
2	Electrical										
2.1	Access to 240V AC Enclosure.	Electrocution.	Panels secured with anti-tamper bolts to ensure doors remain closed. Entire system meets requirements of BS EN60204 standard for electrical safety.	5	1	6	No additional action required.	5	1	6	Pass
2.2	240V AC Equipment Contained within Enclosure.	Smoke/Fire.	Electrical system designed and assessed in accordance with BS EN60204.	1	5	6	No additional action required.	1	5	6	Pass
3	Radiation										
3.1	Light Emitted by Cognex ID Reader when Scanning Panels.	Shock to Operator/Bystanders.	Non harmful LED light source along with short light duration not aimed at the operator.	0	3	3	No additional action required.	0	3	3	Pass
4	Materials/Substances										
4.1	Dust from PCB De-Panelling Process.	Eye/Respiratory Issues.	Vacuum extraction installed under the router bit which collects dust from the PCBs.	0	4	4	Regular maintenance schedule in place by Works Engineering to change extraction bag, with appropriate PPE and training.	0	4	4	Pass
5	Ergonomics										
5.1	Removal and Transport of PCB/Tray Storage Devices.	Strain to Back and Injury to Arms Along with Drop Risk.	Weight of items under 5kg when fully loaded. Handles incorporated into design to allow for two handed lifting.	3	3	6	Recommended storage height of no greater than 1.4m due to handles being on the top side.	3	2	5	Pass
6	Reasonably Foreseeable Actions/Misuse										
6.1	Untrained User Access to Machinery.	Damage to Equipment.	Machinery is password protected to deter from unwarranted use.	0	4	4	No additional action required.	0	4	4	Pass

Table 9 - ATOM Lights-Out Running Risk Assessment

After conducting the risk assessment on the lights-out running solution, all the aspects identified were deemed acceptable. This comprehensive risk assessment involved evaluating various potential hazards associated with the implementation of the new automated system. Each identified risk was meticulously analysed for its severity, likelihood, and potential impact on both operators and the manufacturing process. The evaluation considered mechanical, electrical, and operational risks, ensuring that all necessary safety measures were in place. As a result, mitigation strategies were developed and implemented to address any identified risks, thereby ensuring the system's compliance with industry safety standards.

5.8 Installation & Commissioning

The installation stage of the project is critical to ensuring the implementation of a robust system. The first step of the installation involves physically building the mechanical aspects of the solution. This is carried out by Technicians who assemble the components based on assembly drawings produced by the mechanical engineers. Included in these assembly drawings are the part numbers of the components along with exploded views and fastening requirements. Following the mechanical installation being completed, the next step is the wiring and connection of sensors, actuators, and controllers. This is also completed by Technicians by following the wiring diagram, which can be found in Appendix 4 – Wiring Diagram section of this report. To fulfil the requirements of the machine specification, the guidelines outlined by EN 60204-1:2018 must be followed. Some of the key aspects of this standard include separation between mains and control signal voltages, along with ensuring the correct cable is installed.

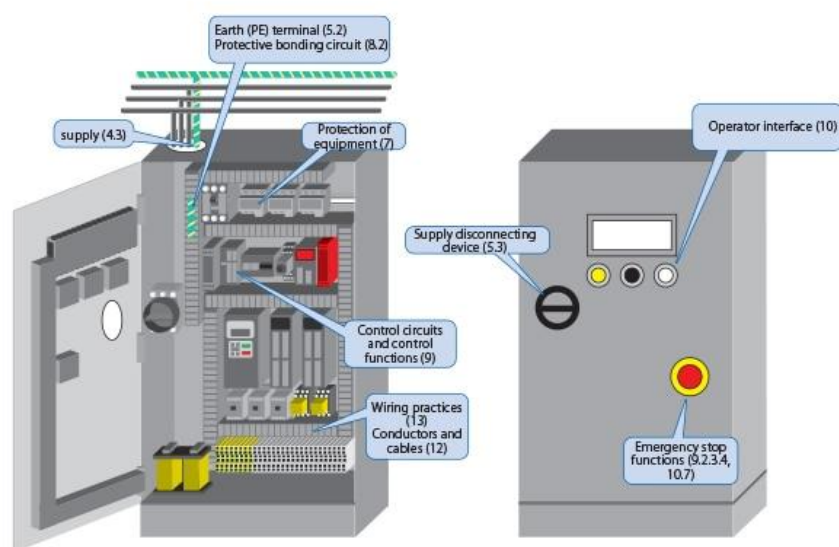


Figure 36 - Example of Control Panel following EN 60204-1:2018

After the completion of wiring and connections, the next phase is calibration. All sensors must be positioned and calibrated to achieve precise measurements. This also involves ensuring the feedback of the sensors to the control system is functioning correctly. The final step of the installation process is verifying that the safety features are operating as expected. In this case, ensuring the operation of the emergency stops and door interlocks is critical to avoid the system only operating in an unsafe condition.

Commissioning of the system commences following the completion of the installation process. This is where the system is powered up and basic functionality checks are carried out. These basic checks include ensuring communication between components followed by verifying actuator movement. Specific parameters can then be optimised specifically, and the speed at which motor positioning routines are carried out. A detailed commissioning guide for the lights-out manufacturing system can be found in Appendix 1 – Commissioning Guide section.

5.9 Testing & Validation

5.9.1 Validation Plan

On completion of the installation and commissioning stage of the project, the testing and validation phase commences. During this, the system is subjected to various production scenarios to ensure it performs as intended. Detailed below, in Table 10, is the testing plan for the lights-out running solution. A minimum quantity of 25 units of each variant must be run through the system during the validation process, which totals 100 units. For the validation process to be deemed successful, a yield of 98% must be achieved.

Reference	Validation Section	Method	Expected Outcome	Actioner	Validated (Y/N)
1	PCB Loading/Unloading				
1.1	PCB Panel Load	Run PCB Loading Sequence	- PCB cassette clamp releases. - Gantry picks PCB from cassette successfully. - PCB is placed from the cassette into the cutting tray. - Four PCB clamps enable to retain panel position prior to cutting. - Proximity sensors detect that PCB clamps have been engaged. - Gantry returns to safe position to avoid collision. With the robot.	ASG Eng	Y
1.2	PCB Panel Unload	Run PCB Unloading Sequence	- Four PCB clamps release panel prior to removal. - Gantry moves to PCB tray and removes empty panel. - Gantry moves to reject position and releases empty panel.	ASG Eng	Y
1.3	PCB Tab Cutting	Run PCB De-Panel Process	- Two PCB tabs are cut in accordance with specified dimensions. See....	ASG Eng	Y
1.4	PCB Cut Quality	Inspect 100% of Units on Vision Scope and Record Images	- Inspect PCB for any signs of damage or burring. - Compare results against acceptance criteria.	ASG Eng	Y
1.5	PCB Contamination	Inspect 100% of Units on Vision Scope Before & After Cutting and Record Images	- PCB cleanliness unchanged before and after cutting process. Refer to for reference images.	ASG Eng	Y
2	Tray Unloading				
2.1	Tray Unloading to Magazine	Run Tray Unloading Process	- Completed tray moves from loading position to the end of the conveyor upon completion. - Tray magazine moves to empty slot position ready to accept parts from the conveyor. - Tray pusher actuates once tray is in unloading positions and successfully transfers tray into the magazine. - -Stacker moves to next slot position ready for to accept another tray of completed parts.	ASG Eng	Y
2.2	Tray Magazine Removal	Unload Tray Magazine from Stacker Once Fully Populated	- Operator is notified that the tray magazine is full and requires removal. - Stacker moves tray magazine to the unloading position for the operator to handle. - System stops producing parts if the magazine is not removed by the time another tray of parts is built.	ASG Eng	Y

Table 10 - ATOM Lights-Out Manufacturing Validation

"Validation outcomes are critical in quality control, as they confirm that a process or system meets its intended purpose and performs reliably under specified conditions" (Juran & Godfrey, 1999). Following the successful completion of the validation aspects outlined, all the intended outcomes were achieved. The results of the validation ensure that the system is now nearly production-ready, and the process can be fully implemented into the process. Some other factors that need to be considered before full implementation include approval from the appropriate personnel. At Renishaw Process Change Authorisation (PCA) requests are managed through Syteline. This will be completed by the Production Engineers before the system can be used for production. Another factor that needs to be taken into consideration before production usage is training requirements. This responsibility also falls to Production Engineers, who will need to ensure that user documentation such as Work Instructions is updated to reflect the modified process.

5.9.2 Modified Process Data Analysis

While it is important to test and validate the functionality of the system, it is also critical that the production metrics are analysed. This is to ensure that the developments made have overall improved the system efficiency, which was the goal of implementing the lights-out solution in the beginning. Based on the work carried out in the Results & Analysis section of this report, the same tools can be utilised to assess the effectiveness of the systems post-introduction into the production environment.

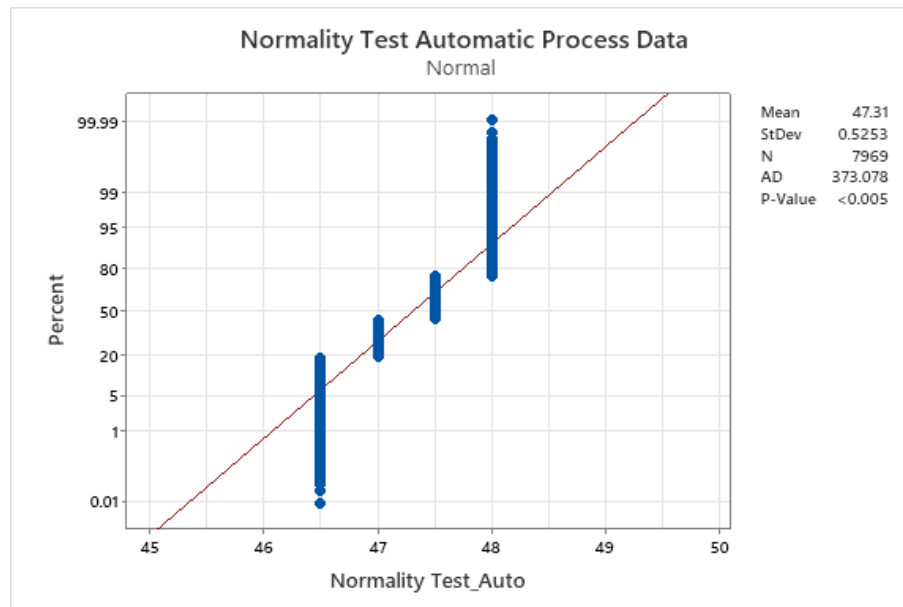


Figure 37 -Normality Test Lights-Out Process Data

After conducting a normality test, shown in Figure 37, on the data captured post-implementation of the lights-out running system, the results still did not conform to a normal distribution. Even though this was the case, it was clear that there was less variation in the results, compared to before the system was introduced. Figure 38 below shows the Goodness of Fit Test performed on the lights-out production data.

Goodness of Fit Test

Distribution	AD	P	LRT	P
Normal	373.078	<0.005		
Box-Cox Transformation	371.746	<0.005		
Lognormal	373.753	<0.005		
3-Parameter Lognormal	373.134	*	0.000	
Exponential	3577.703	<0.003		
2-Parameter Exponential	2235.682	<0.010	0.000	
Weibull	398.417	<0.010		
3-Parameter Weibull	390.068	<0.005	0.000	
Smallest Extreme Value	400.668	<0.010		
Largest Extreme Value	415.404	<0.010		
Gamma	373.567	<0.005		
3-Parameter Gamma	3118.002	*	0.000	
Logistic	355.900	<0.005		
Loglogistic	356.381	<0.005		
3-Parameter Loglogistic	355.900	*	0.001	

Figure 38 - Goodness of Fit Test (Lights-Out Data)

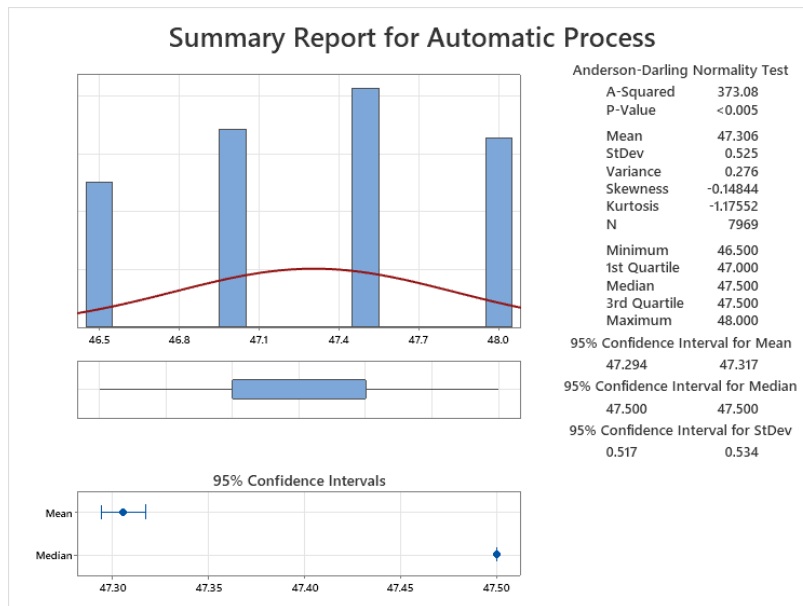


Figure 39 - Analysis Summary Lights-Out Data

Utilising the Anderson-Darling Normality Test the histogram, shown in Figure 39, displays a more uniform distribution compared to before the lights-out solution was implemented. The likely cause of this difference in distribution is a reduced cycle time for the units to be manufactured, due to the removal of human intervention within the process.

Boxplot of Automatic Process

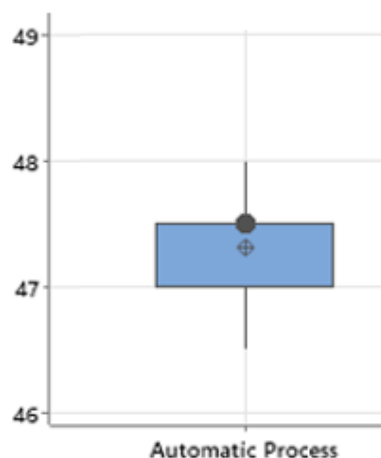


Figure 40 - Box & Whisker Plot of Lights-Out Data

Figure 40 illustrates the Box and Whisker Plot, using the data captured following the implementation of the lights-out system. This diagram shows that tighter cycle times have been achieved with the implementation of the lights-out running, along with the elimination of outliers identified in the original analysis. It was determined originally that the cause of the outliers in the Box and Whisker Plot was increased cycle times due to slow panel changes by operators. With the removal of this process, the outliers have also been eliminated.

6 Conclusion

The ATOM Encoder Lights Out Manufacturing has successfully demonstrated the feasibility and benefits of implementing lights-out manufacturing in the production of ATOM encoders at Renishaw. This conclusion synthesises the key findings, implications, and recommendations derived from the study.

The study began with exploring automation and its historical impact on manufacturing processes. Renishaw's commitment to innovation and precision in manufacturing was highlighted, particularly through the production of ATOM encoders. The primary aim was to investigate the potential for lights-out manufacturing—a process that allows for continuous operation with minimal human intervention.

The literature review provided insights into the benefits and challenges of lights-out manufacturing. Benefits such as increased efficiency, cost savings, and improved safety were emphasised. However, challenges such as high initial costs and the need for reliable equipment were also noted. These insights framed the context for assessing the feasibility of implementing such a system at Renishaw.

Data collection and analysis focused on understanding the current manufacturing process, specifically identifying bottlenecks and inefficiencies caused by human intervention. The study revealed that tasks such as loading PCBs and unloading trays significantly contributed to increased cycle times and variability in production efficiency.

The design phase involved specifying the technical requirements for a lights-out manufacturing system. Key technologies identified included servo motor actuators, machine vision, and advanced control systems. Mechanical and electrical components were selected to ensure high precision and repeatability. Safety and compliance were paramount, with all components meeting relevant standards and regulations. The implementation phase focused on integrating these components into the existing manufacturing process. Mechanical solutions for PCB loading and tray unloading were developed, involving precise actuators and robust control systems. The electrical integration ensured seamless communication between components, enhancing the system's reliability.

The testing phase involved subjecting the system to various production scenarios to ensure it performed as intended. The validation process confirmed that the lights-out solution met the desired outcomes, achieving a high yield and consistent performance. The reduction in cycle time variability and the elimination of outliers caused by human intervention were significant improvements.

The successful implementation of lights-out manufacturing for ATOM encoder production has several implications. These include increased efficiency, achieved by the automation of loading and unloading tasks. This has streamlined the production process, reduced cycle times and increased overall efficiency. The implementation has also provided cost savings, by minimising human intervention and significantly reducing labour costs. It “not only streamlines operations but also leads to significant cost savings by reducing waste and improving resource efficiency” (Bamber, Sharp, & Hides, 2000). Additionally, the continuous operation capability maximises the use of equipment, further enhancing cost efficiency. Improved quality has also been achieved, by the ensure the automation systems employed provide consistent and precise handling of components, leading to improved product quality and reduced variability. Lights out running enhances safety aspects by minimising human interaction with machinery, which in turn reduces the risk of workplace injuries, creating a safer working environment.

Based on the findings of the report, several recommendations are proposed for Renishaw considering lights-out manufacturing. These include investment in reliable equipment to ensure that the components selected for automation are reliable and meet industry standards. This reduces downtime and maintenance costs in the long run. Also, continuous monitoring and improvement of production metrics. This data could be used to identify further areas for improvement and optimise the process. Finally, future research and development to refine the lights-out manufacturing processes. This could include exploring advanced robotics and AI-driven processes. "Value stream mapping is a powerful tool for identifying and eliminating waste, which directly contributes to increased efficiency and more streamlined production processes" (Rother & Shook, 2003). Other lean manufacturing tools like this could also be employed to identify further improvements. "Industry 4.0 technologies enable lean automation by integrating cyber-physical systems, which enhance flexibility, efficiency, and responsiveness in manufacturing processes" (Kolberg & Zuhlke, 2015). Concepts associated with Industry 4.0 could potentially be investigated to further enhance the system.

The project has validated the hypothesis that lights-out manufacturing can significantly enhance the efficiency, cost-effectiveness, and safety of the ATOM encoder production process at Renishaw. The successful implementation of the system has provided a model for future automation projects within the company and across the industry. Embracing such innovative manufacturing strategies will be key to maintaining competitive advantage and driving future growth in the highly competitive field of precision engineering.

In conclusion, the transition to lights-out manufacturing represents a significant step forward for Renishaw, embodying the company's commitment to innovation and excellence in manufacturing. The insights and recommendations from this project offer a roadmap for further advancements, ensuring that Renishaw remains at the forefront of technological innovation in the manufacturing sector.

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Appendix

Appendix 1 – Commissioning Guide

1 Mitsubishi PLC & HMI Setup

This section of the report covers the PLC and HMI code transfer which should be performed at the beginning of the commissioning process. The latest version of the code can be found in the following repository on Azure DevOps:

[T-95176_ATOM_PCB2B_Duplication](#)

1.1 PLC

1.1.1 GX Works 2

To transfer the code to the PLC CPU, open the 'GX Works 2' project that can be found in the repository. Ensure that the IP address is set correctly for the PCB to Body platform that is being commissioned. This can be done by heading to 'Parameter' then 'PLC Parameter' in GX Works 2 as shown in Figure 1 below.

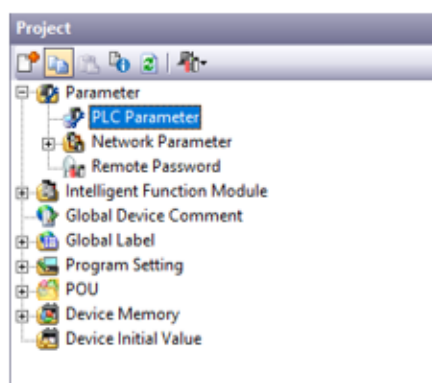


Figure 1 - PLC Parameter

After opening the 'PLC Parameter' head to the 'Built-in Ethernet Port Setting' tab as follows in Figure 2.

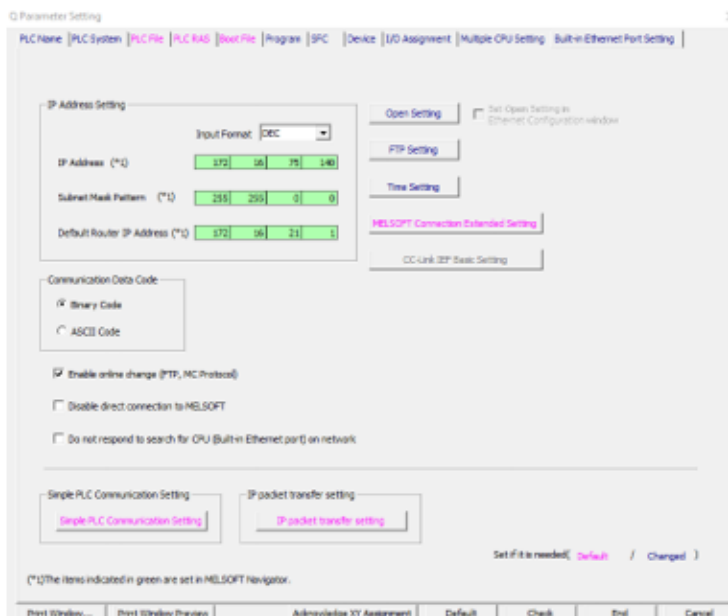


Figure 2 - Built-in Ethernet Port Setting

The IP address should be set to one of the following depending on the platform being commissioned.

Set 3 & 4 PCB to Body PLC IP Addresses			
Robot Set	IP Address	Subnet Mask	Default Gateway
Set 3 (RUK	172.016.075.140	255.255.0.0	172.016.021.001
Set 4 (RUK	172.016.075.170	255.255.0.0	172.016.021.001

Table 1 - Set 3 & 4 PCB to Body PLC IP Addresses

Once the IP address has been confirmed to be correct the connection destination must then be configured correctly to ensure the code is transferred to the correct PLC. Head to the 'Connection Destination' section in 'GX Works 2' as shown below in

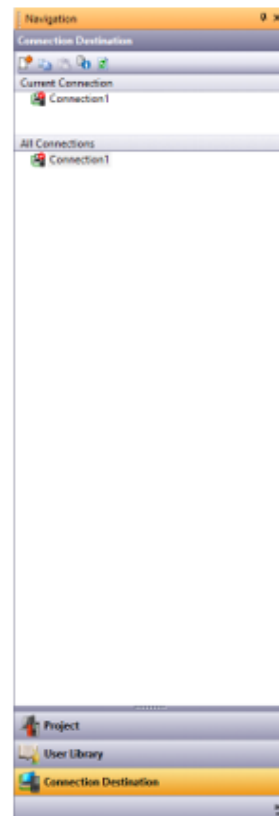


Figure 3 - Connection Destination

Double-click on 'Connection 1' for the following pop in Figure 4 to be displayed.

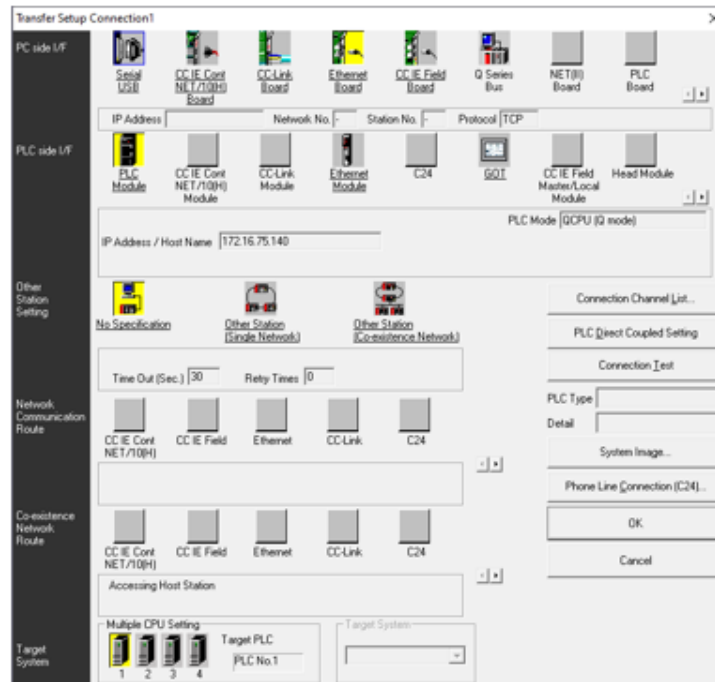


Figure 4 - Transfer Setup

Depending on which connection method is required it may be necessary to adjust the transfer setup options. Figure 4 shows the 'Ethernet Board' transfer setup option where the PLC is connected to via the network. If connecting to the PLC via this option, ensure that the IP address is set correctly within the transfer setup configuration. If it needs to be amended double-click the 'PLC Module' button and the following should appear.

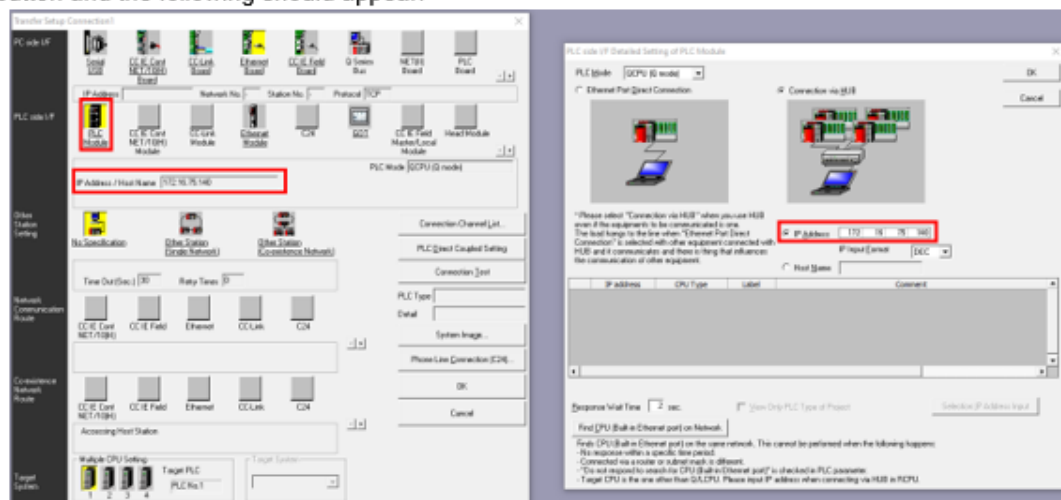


Figure 5 - Transfer Setup Detailed Setting

Change the IP address if necessary and then perform a 'Connection Test' to make sure that the PLC can be communicated with. Once successful click the 'OK' button to continue. Alternatively, the PLC can be communicated with via USB. Simply connect to the PLC CPU using a USB cable and configure the transfer setup screen as shown in Figure 6 and perform a connection test.

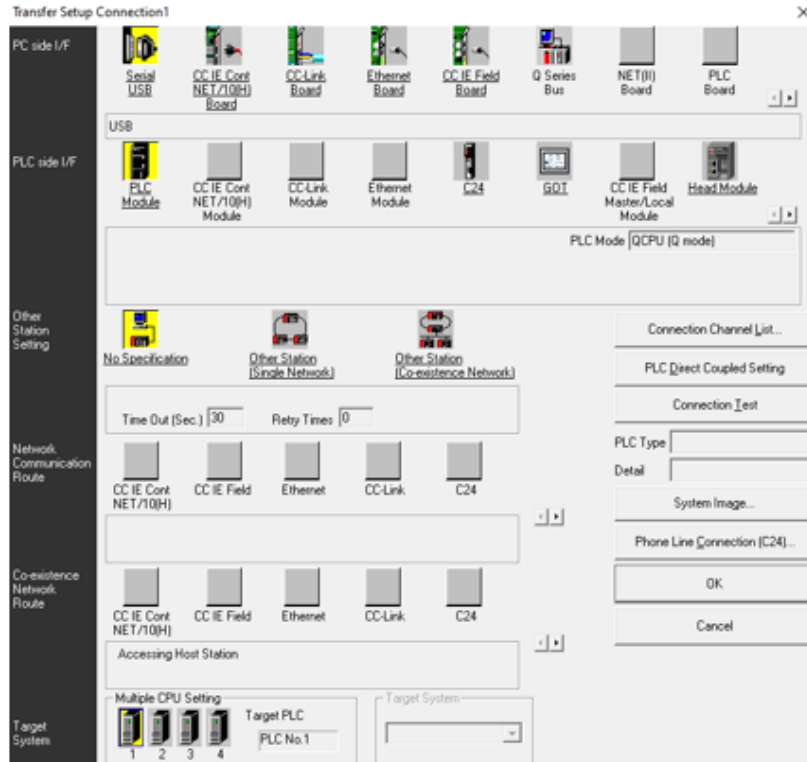


Figure 6 - USB Transfer Setup

Once the transfer setup has been completed and a successful connection test has been performed the code can now be transferred to the PLC. Select the 'Write to PLC' button as shown in Figure 7.



Figure 7 – Write to PLC

The following pop-up should appear shown in Figure 8. Select the 'Program' and 'Parameter' tick boxes within the below screen. After doing so select the 'Execute' button to proceed.

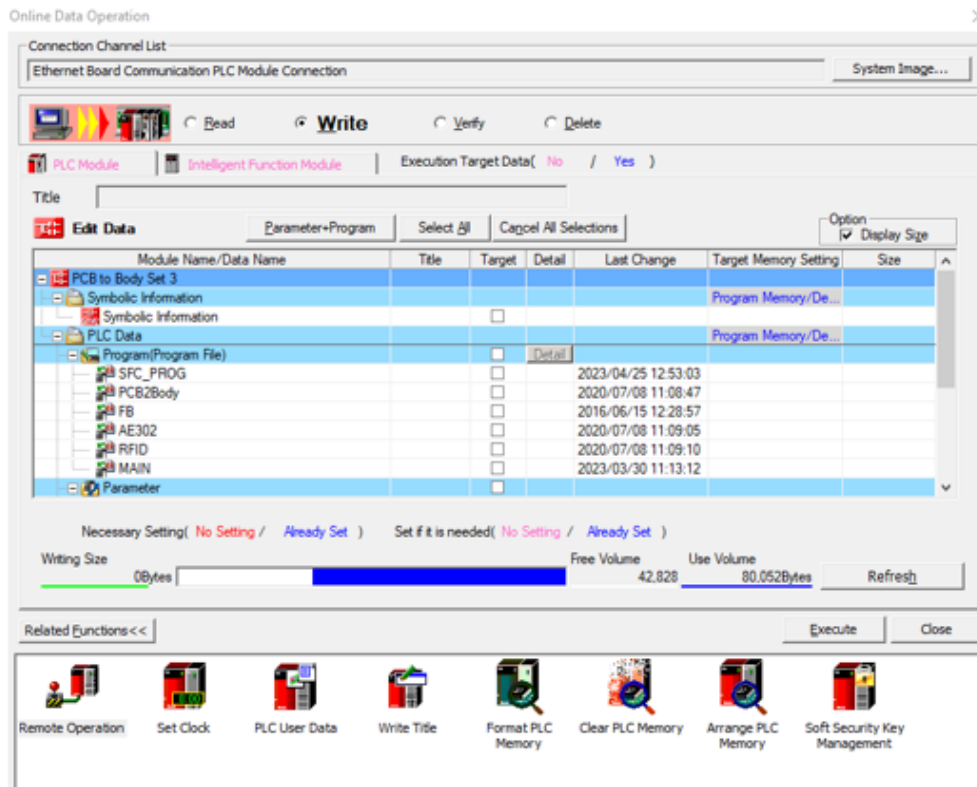


Figure 8 - PLC Write Communication

Once the PLC write has been executed continue through the transfer process by selecting the appropriate option on the dialogue boxes that pop-up. A dialogue box will appear to indicate to the user that the write has been completed successfully.

1.1.2 Simple Motion Module Setting Tool

Now that the PLC write has been completed another code transfer needs to be performed however, this time specifically to the 'QD77MS4' module. The purpose of this module is servo motor control. To transfer the code to the servo control module, open the 'Simple Motion Module Setting Tool' file within the repository. After opening the file successfully head to the 'Online' tab and select the 'Transfer Setup' option shown below.

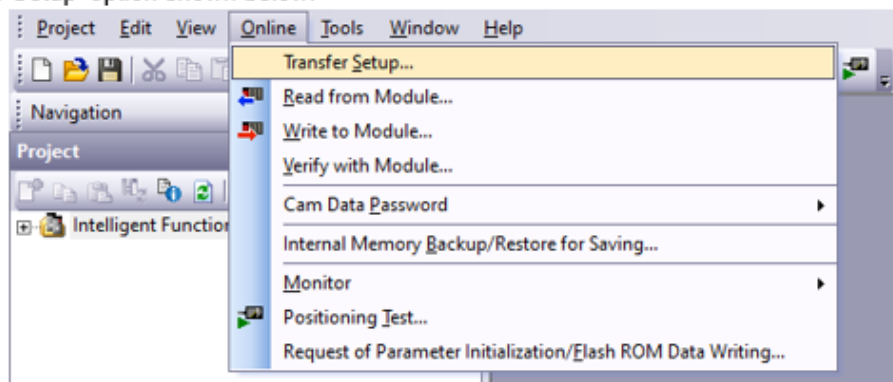


Figure 9 - Simple Motion Transfer Setup

Follow the exact same process detailed in section 1.1.1 of this document to configure the transfer setup correctly. Once the transfer setup has been configured select the 'Write to Module' option. The following screen will appear shown in

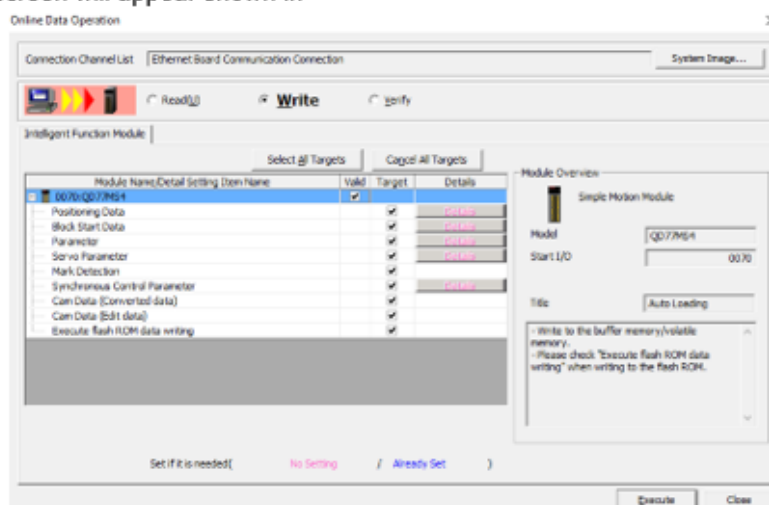


Figure 10 - Simple Motion Write Communication

Ensure that the 'Valid' and all the 'Target' tick boxes are selected before executing the write operation. Once all the appropriate options have been selected proceed by using the 'Execute' button. Various dialogue boxes will appear after executing the write command. Select the appropriate option to the prompts until the process has been completed. It is critical to power cycle the PLC and servo drives after completion of the previous steps. This can be done via the isolator switch on the electrical panel. After powering off the machine wait 10 seconds before turning the power back on.

1.2 HMI

After completing the PLC code transfer procedure, the next stage involves transferring the code to the HMI. This is done via the 'GT Designer3' software. Open the HMI file in the repository and head to the system tab shown in Figure 11.

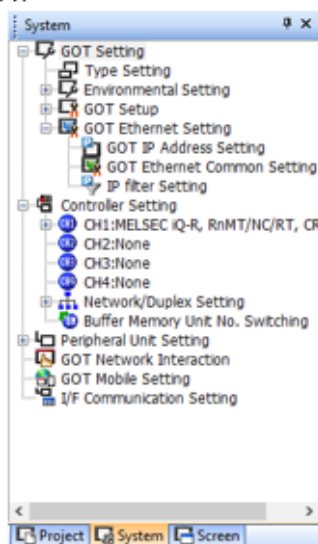


Figure 11 - HMI System Settings

Select the 'GOT Ethernet Setting' drop down and open the 'GOT IP Address Setting' to configure the HMI IP address correctly. This will correspond to the PCB to Body platform that the commissioning task is being carried out on. See Table 2 below for the necessary information.

Set 3 & 4 PCB to Body HMI IP Addresses			
Robot Set	IP Address	Subnet Mask	Default Gateway
Set 3 (RUK)	172.016.075.141	255.255.0.0	172.016.021.001
Set 4 (RUK)	172.016.075.171	255.255.0.0	172.016.021.001

Table 2 - Set 3 & 4 PCB to Body HMI IP Addresses

If the HMI IP address is incorrect for the platform currently being configured it may be necessary to amend it through 'MELSOFT Navigator'. Figure 12 below demonstrates how to check with the HMI IP address is configured correctly.

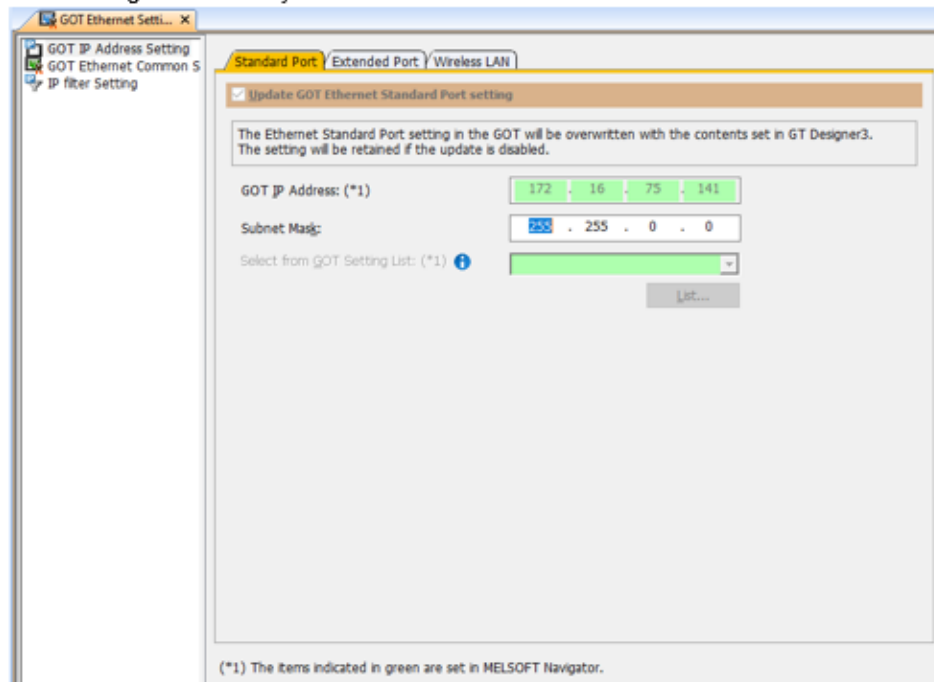


Figure 12 - HMI IP Address Setting

Now that the IP address for the HMI has been configured correctly head to the 'Communication' tab within 'GT Designer3' as shown in Figure 13.



Figure 13 - Write to GOT

After selecting 'Write to GOT' the following screen will appear shown in Figure 14. Depending on the connection method either select 'Ethernet' or 'USB'. If connecting via ethernet ensure that the IP address matches the platform being configured. Use the 'Test' button to establish a connection to the HMI. If a successful connection is established proceed by clicking 'OK'.

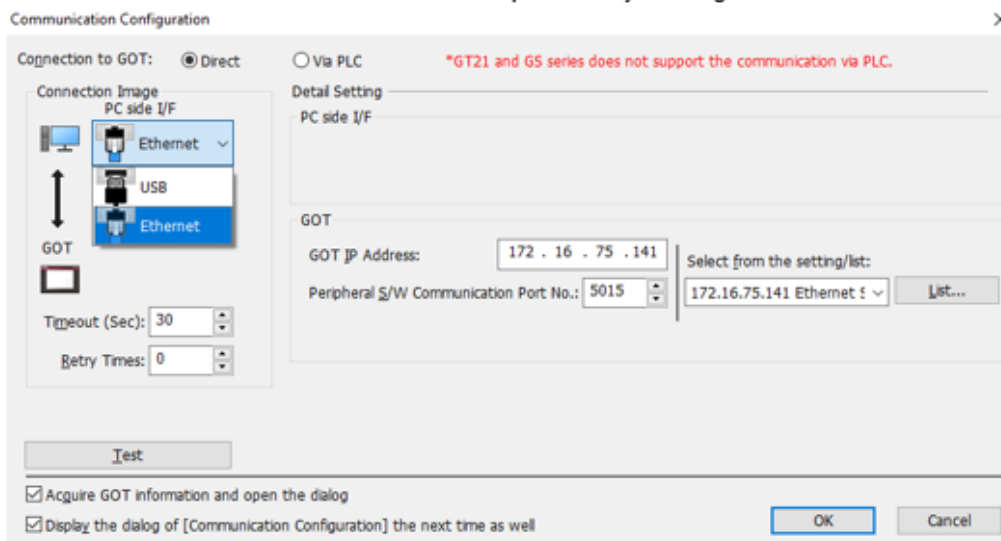


Figure 14 - HMI Communication Configuration

Before completing the 'GOT Write' check that the 'Package Data' drop down has been selected. Once the appropriate option has been selected use the 'GOT Write' button to complete the transfer process. A dialogue box will appear to indicate the successful completion of the HMI write.

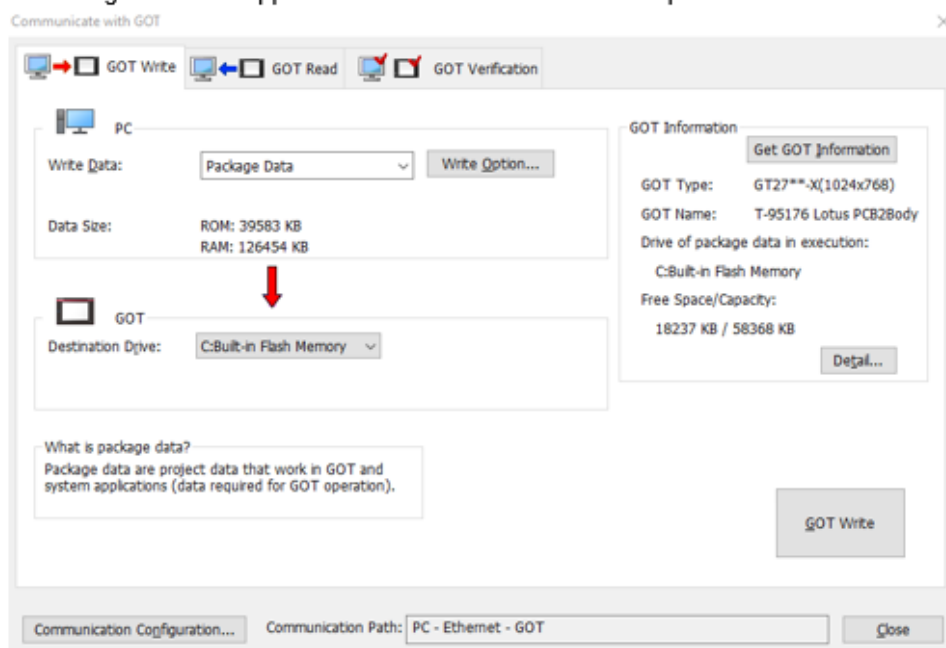
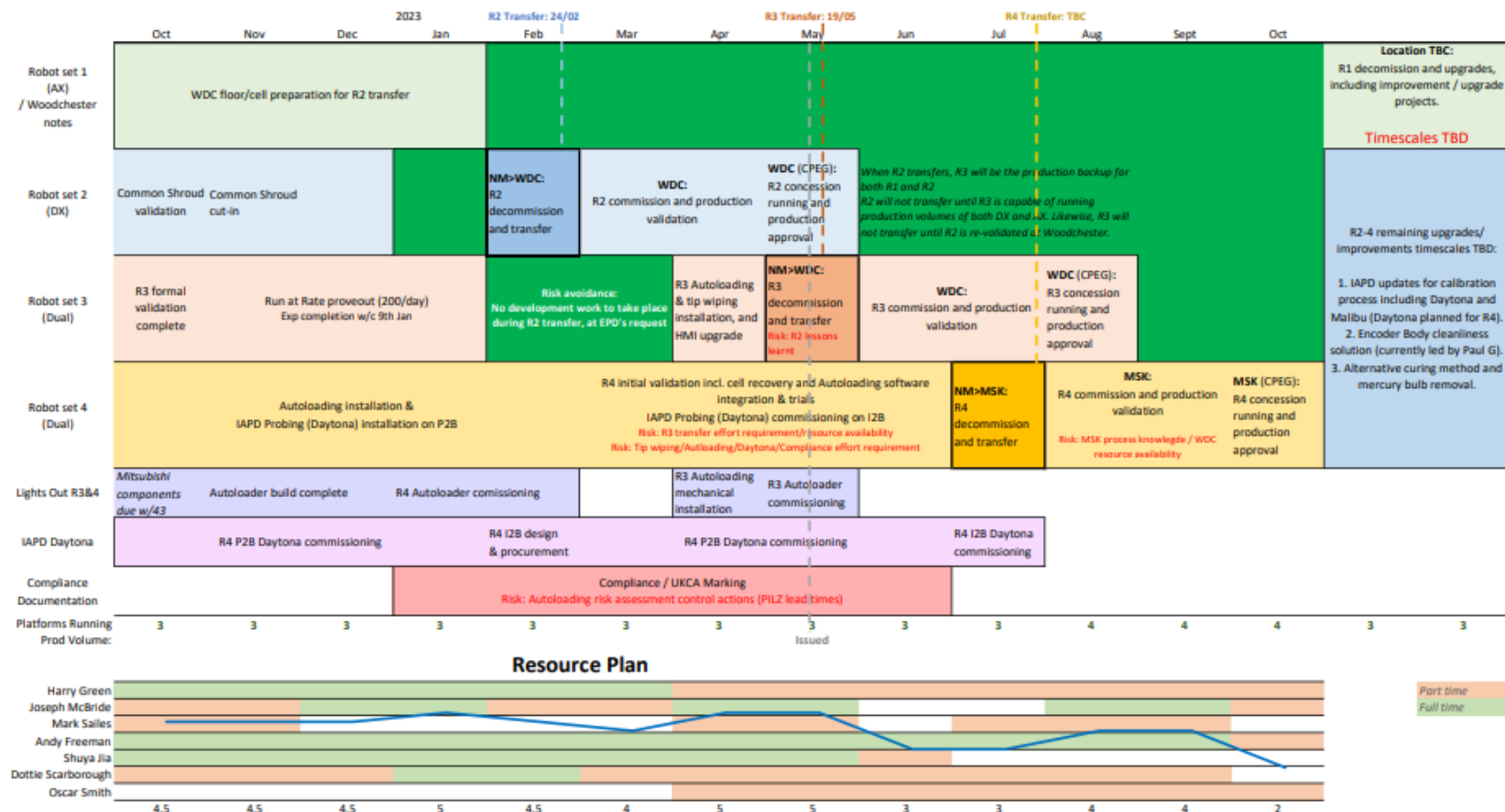


Figure 15 - GOT Write

Appendix 2 – Project Plan

ATOM Robot Duplication Top Level Timeline

15/05/2023

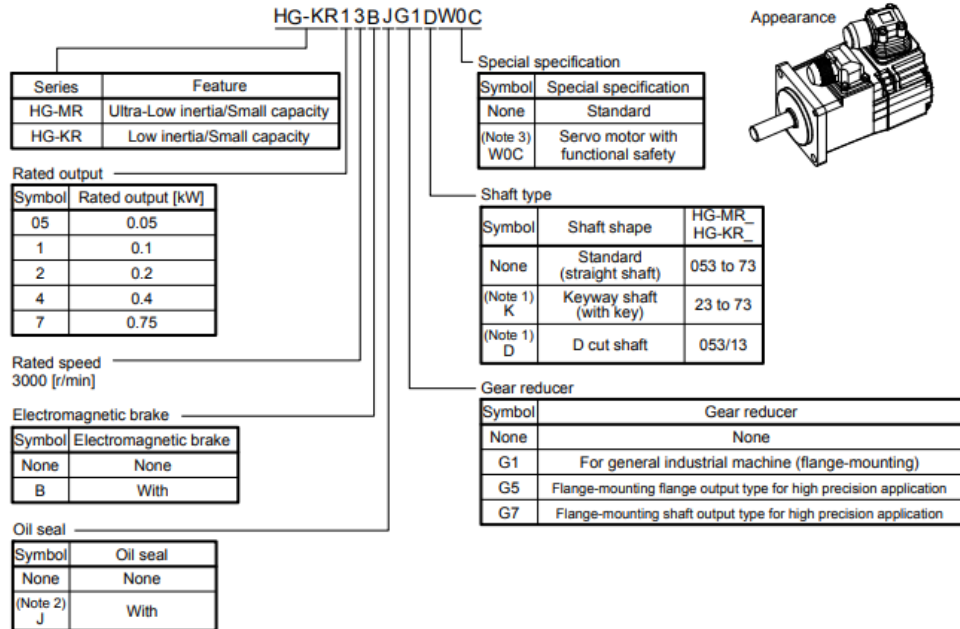


[illegible]

This chapter provides information on the servo motor specifications and characteristics. When using the HG-MR/HG-KR series servo motor, always read the Safety Instructions in the beginning of this manual and chapters 1 to 5, in addition to this chapter.

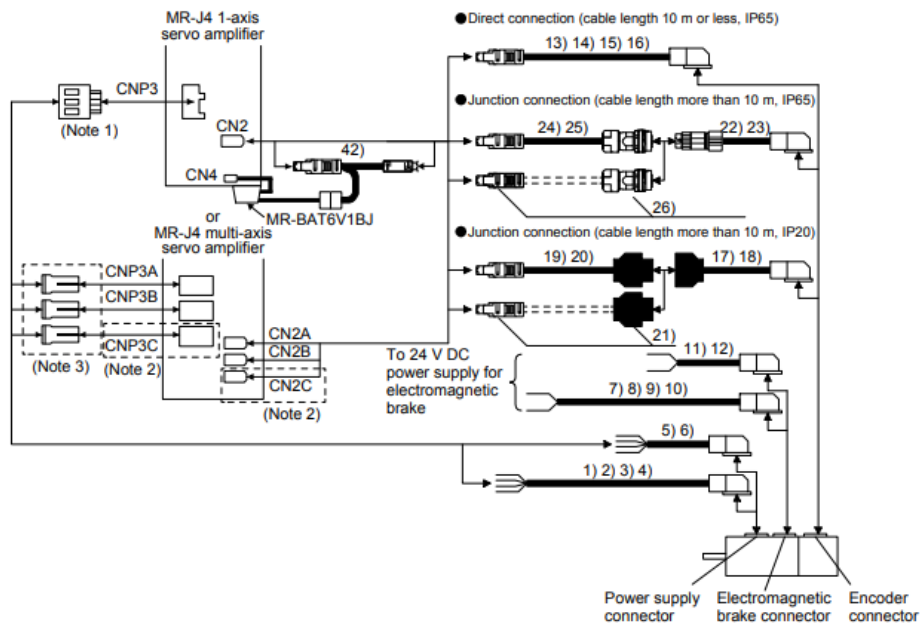
6.1 Model code definition

The following describes what each block of a model name indicates. Not all combinations of the symbols are available.



5.1.1 Combinations of cable/connector sets

(1) HG-MR series/HG-KR series servo motor



- Note 1. Connectors for 3.5 kW or less. For 5 kW or more, it is a terminal block.
 2. This connection is for the MR-J4 3-axis servo amplifier.
 3. Refer to app. 7 for the crimp connector for CNP3_.

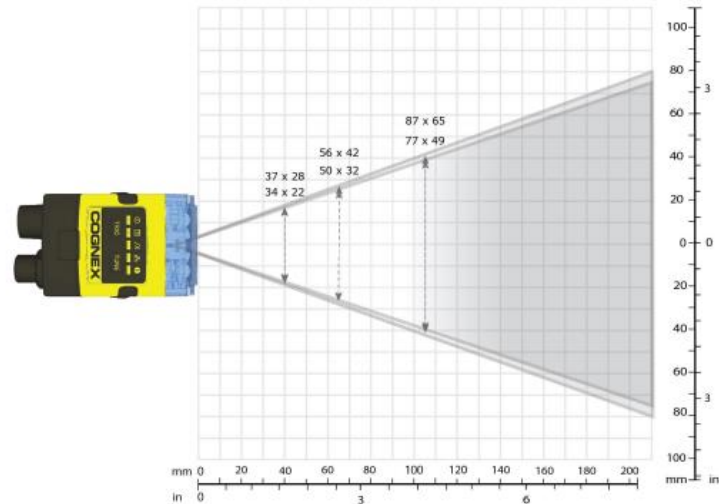
(Mitsubishi Electric, 2024)

Field of View and Reading Distances

DataMan 260 Readers with a 6.2 mm Lens

Short Range (Focused to 105 mm)

The following map shows the FoV of the DataMan 260 series readers with a 6.2 mm lens. Outer FoV values refer to DM262, inner FoV values refer to DM260.



The following tables show the Field of View (FoV) widths of the 6.2 mm lens focused to 105 mm at various distances.

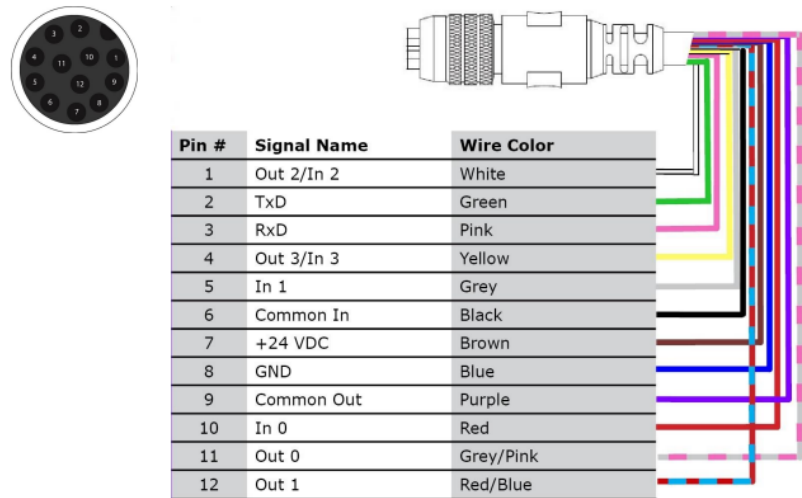
Device	Distances in mm	2D min. code	1D min. code
DM260	40	4 MIL	2 MIL
	65	5 MIL	3 MIL
	105	10 MIL	6 MIL
Device	Distances in mm	2D min. code	1D min. code
DM262	40	3 MIL	2 MIL
	65	4 MIL	2 MIL
	105	7 MIL	5 MIL

5m I/O Breakout Cable (CCB-M12x12Fy-xx)

The I/O cable provides access to trigger and high-speed outputs. You can clip unused wires short or use a tie made of non-conductive material to tie them back.

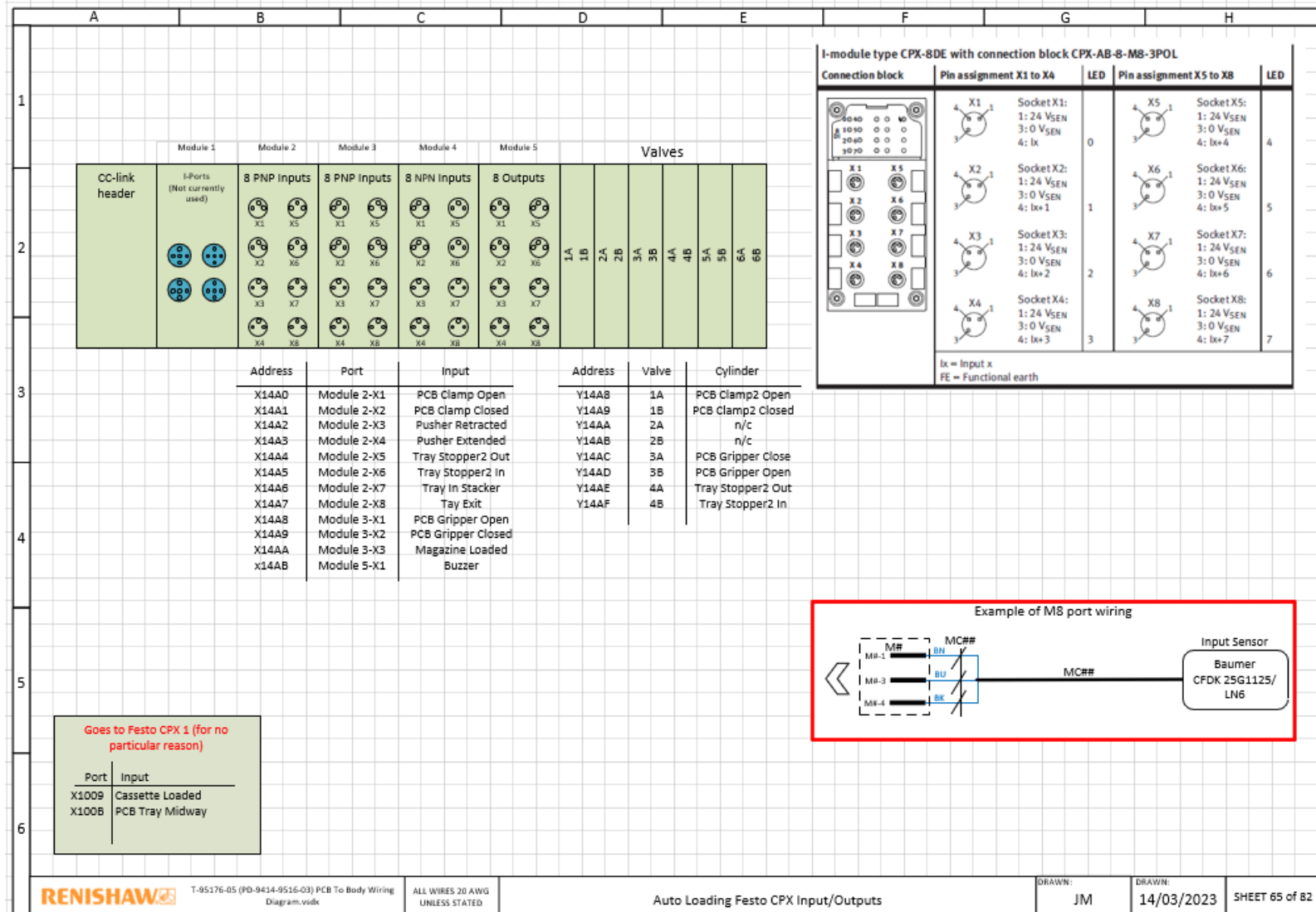
For RS-232, use the Power Supply return path for ground.

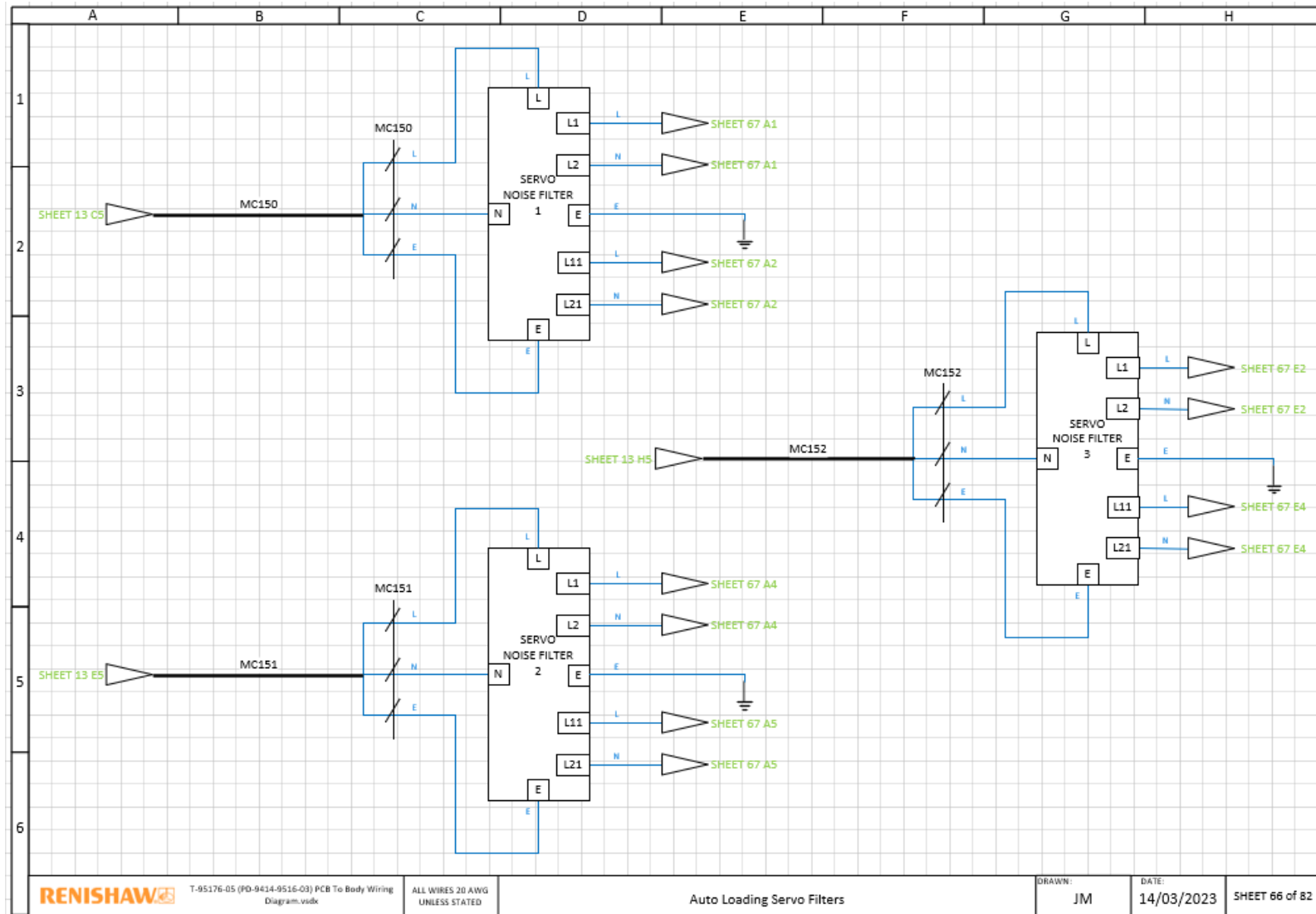
The drawing on the left shows the plug on the device.

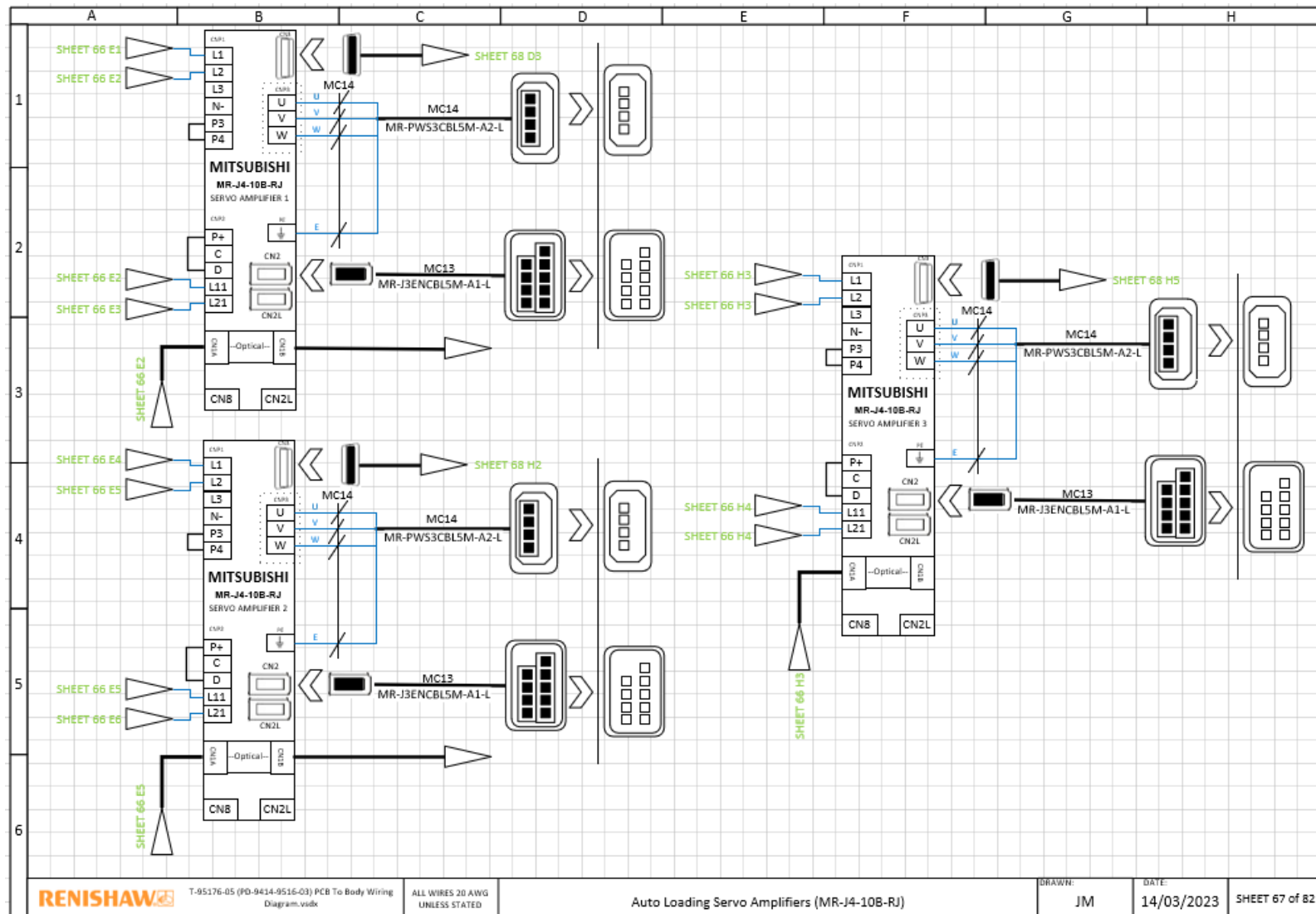


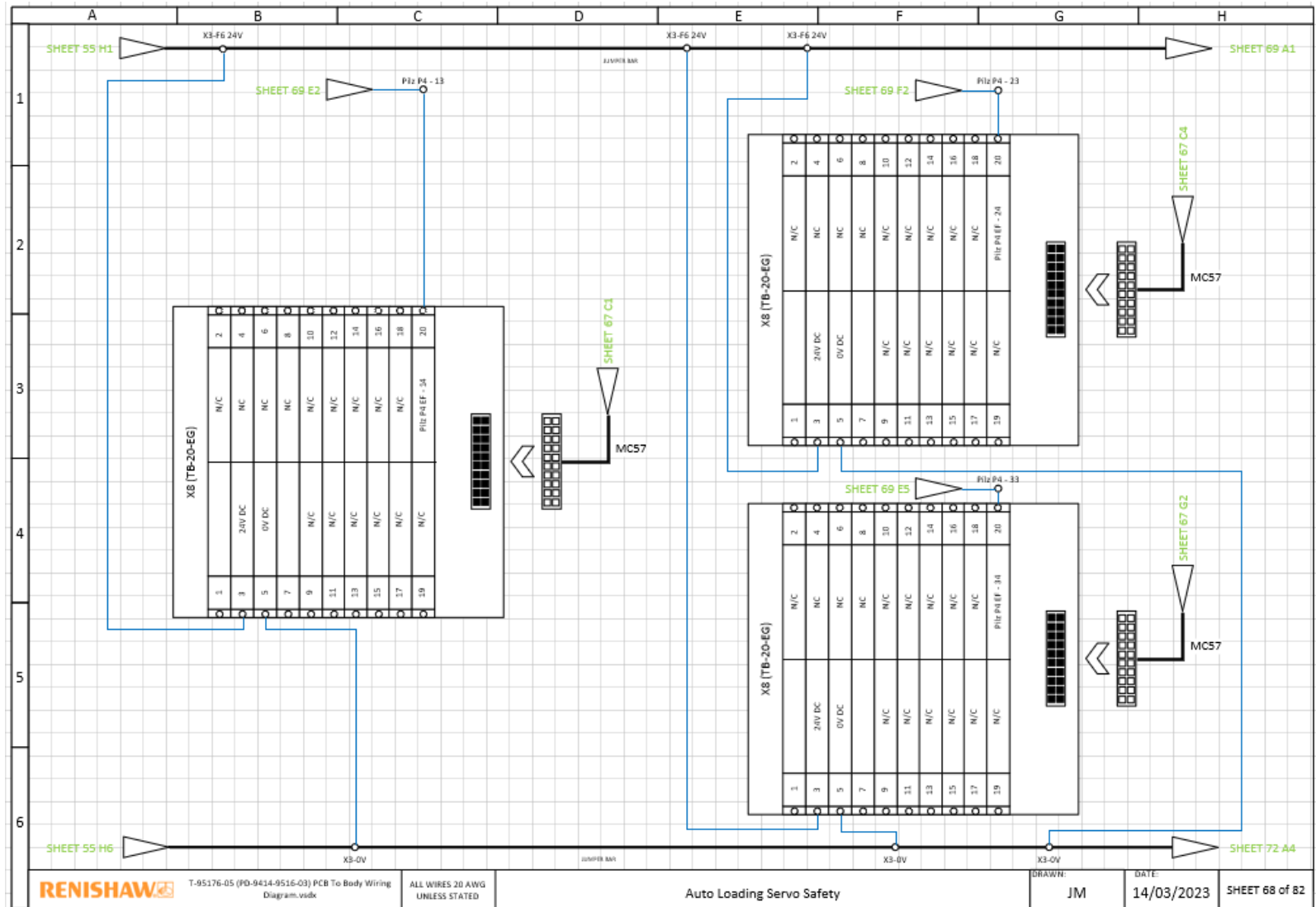
(Cognex, 2024)

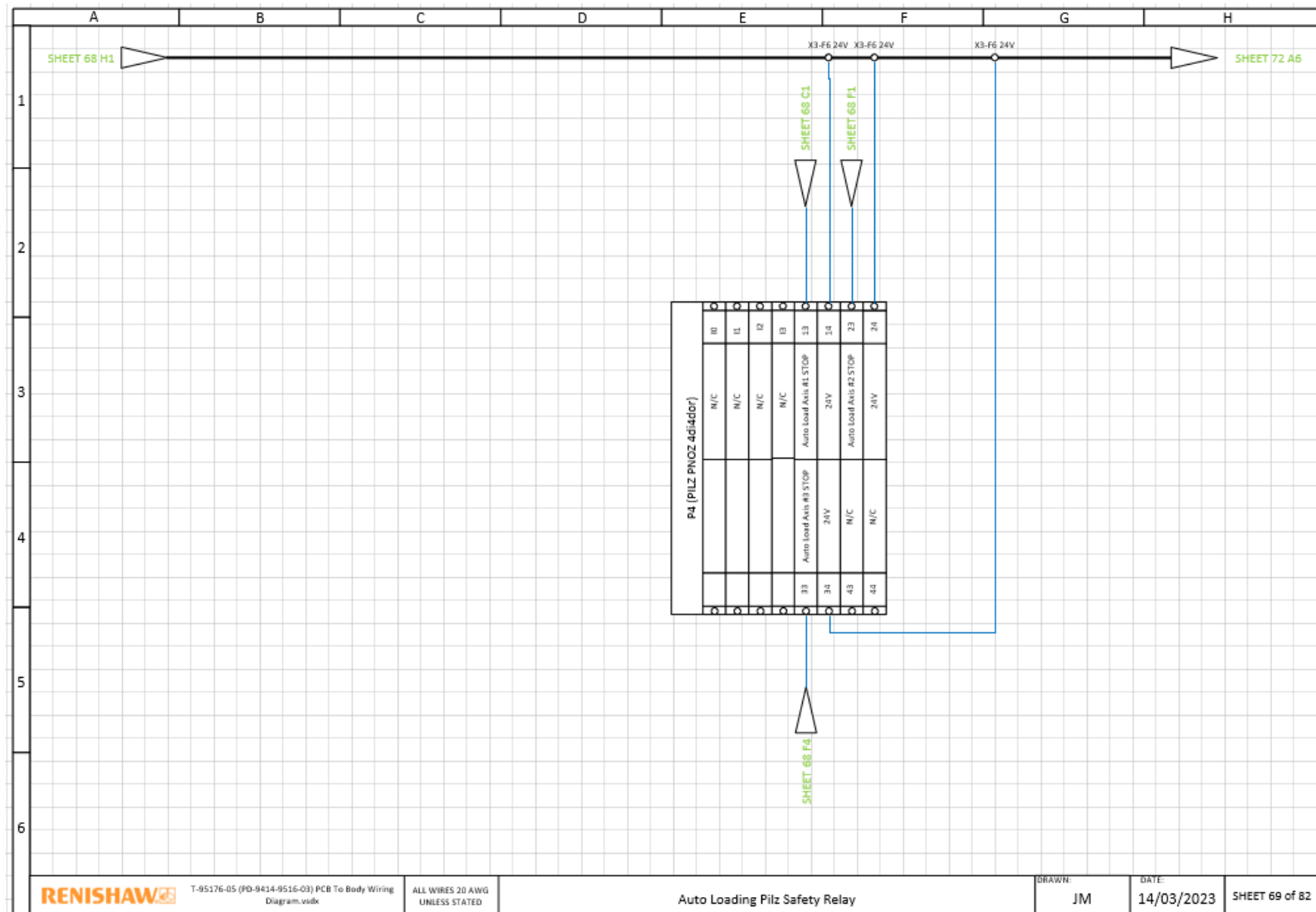
Appendix 4 – Wiring Diagram

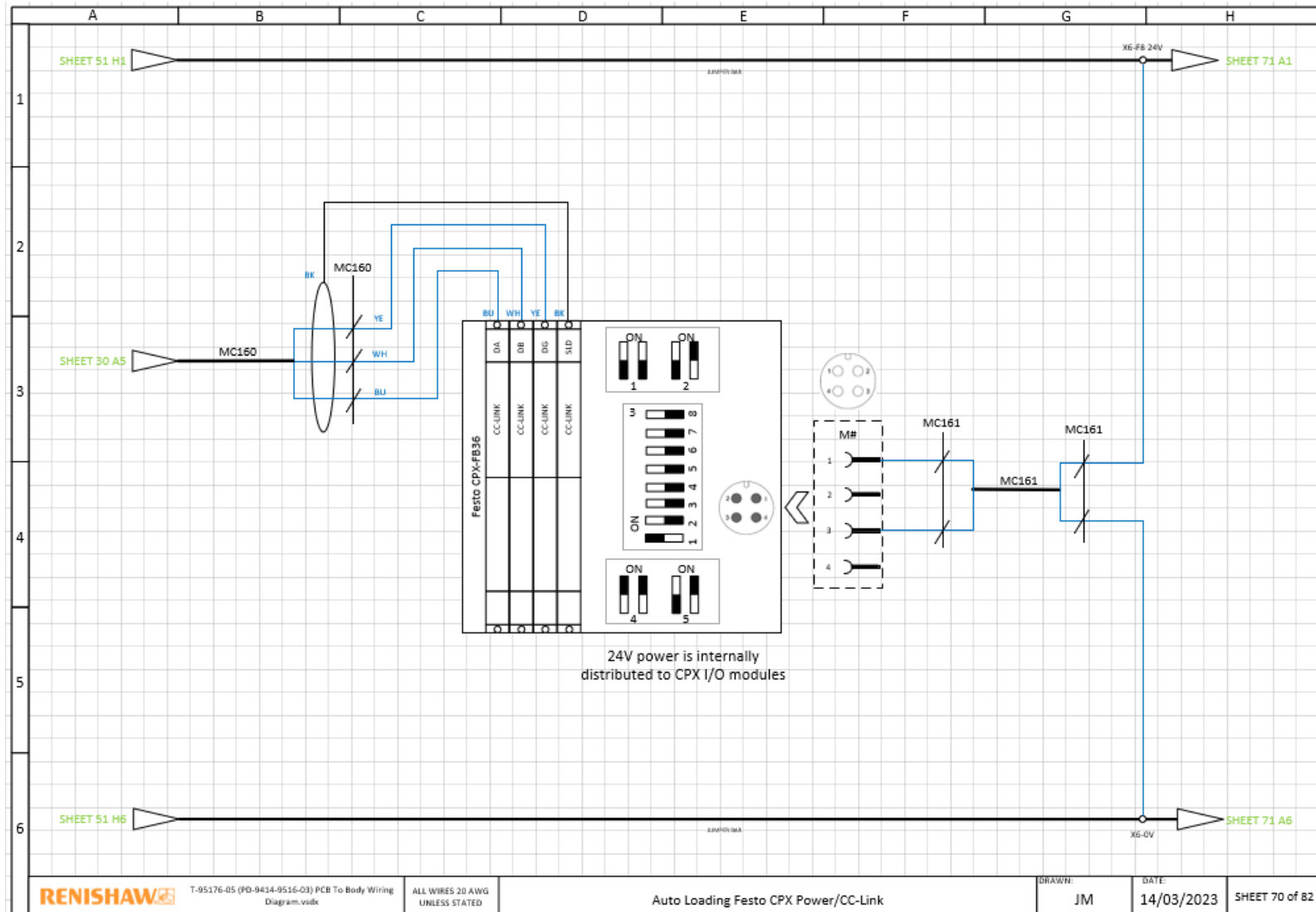


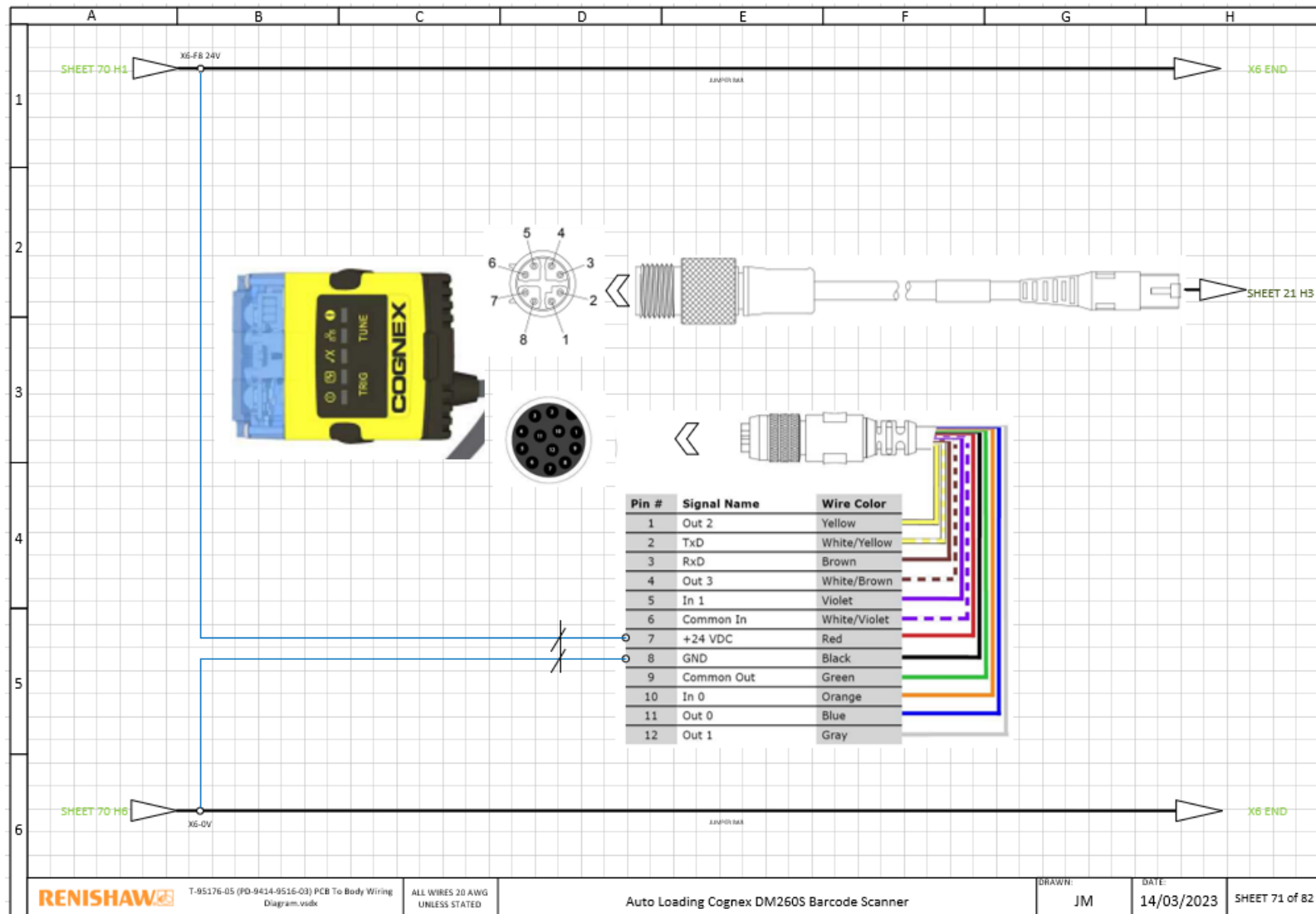






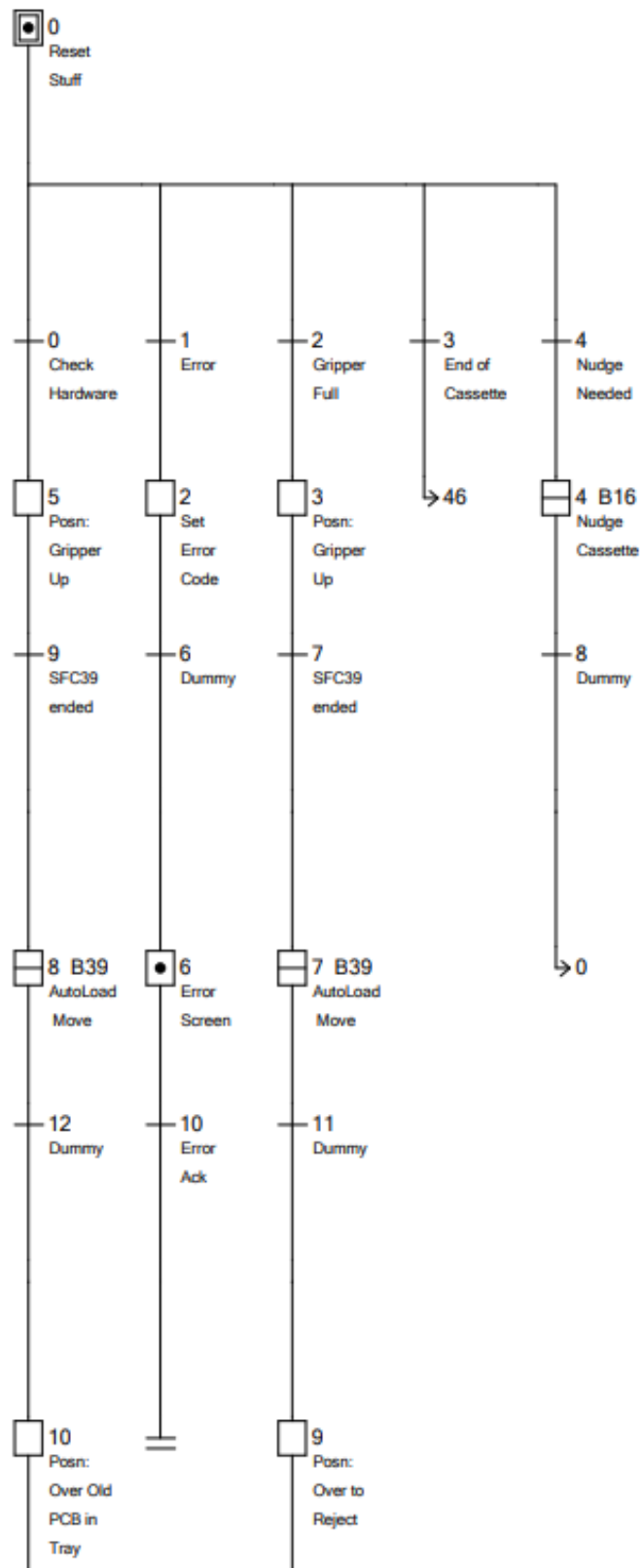






Appendix 5 – PLC and HMI Code Example

SFC



Ladder



HMI

Home
 Back

Close Doors!

Manual Loading
 Auto Loading

Axis 1

Axis 2

Grip PCB

Cassette Open

M1040 DM260 Trigger SFC

PCB Tray out Sequence

Release PCB

Cassette Close

☐ Tray at Midway
☐ Cassette Loaded

Cassette Index

56

Nudge Complete Flag

☐

Variable Position Control

Removeable Stack

PCB Cassette

Mitsubishi Axes Setup

Axes Setup

Axis Position Select

1= Gripper 2= Slide 3= Stacker

Axis Select

6

Axis 1 Position No

456

Axis 2 Position No

456

Axis 3 Position No

456

Axis 1 Position

Axis 2 Position

Axis 3 Position

Move SFC M1039

Mitsubishi Axis Control

PLC Ready

Servo ON

☐ PLC Ready
☐ Axis 1 Ready
☐ Axis 2 Ready
☐ Axis 3 Ready
☐ Axis 1 Servo ON
☐ Axis 2 Servo ON
☐ Axis 3 Servo ON
☐ Axis 1 Error
☐ Axis 2 Error
☐ Axis 3 Error

Axis Jog Speed Limit (mm/min)

Ax#1

1234.56

Ax#2

1234.56

Ax#3

1234.56

Axis 1

Posn Start Number

456

Posn Start

Axis Stop

Axis 1 STOP

Axis 2

Posn Start Number

456

Posn Start

Axis 2 STOP

Axis 3

Posn Start Number

456

Posn Start

Axis 3 STOP

☐ Ax#1 Posn Complete
☐ Ax#2 Posn Complete
☐ Ax#3 Posn Complete

Axis Jog Operation

Axis 1

Axis 2

Axis 3

↓

↑

←

→

↓

↑

Mitsubishi Error Reset

Axis 1 Error Reset

Axis 2 Error Reset

Axis 3 Error Reset

Removeable Stack Slot Positions

Current Posn +12345.6 μm

JOG Up/Down

↓

↑

Inc Move Value +12345.6 μm

		1mm	0.1mm	0.01mm
SLOT 1	.0 μm	- +	- +	- +
SLOT 2	.0 μm	- +	- +	- +
SLOT 3	.0 μm	- +	- +	- +
SLOT 4	.0 μm	- +	- +	- +
SLOT 5	.0 μm	- +	- +	- +
SLOT 6	.0 μm	- +	- +	- +
SLOT 7	.0 μm	- +	- +	- +
SLOT 8	.0 μm	- +	- +	- +
SLOT 9	.0 μm	- +	- +	- +
SLOT 10	.0 μm	- +	- +	- +
SLOT 11	.0 μm	- +	- +	- +
SLOT 12	.0 μm	- +	- +	- +

Run Belt Only

Extend Pusher

Retract Pusher

69

