MANU2453: Robotic Workcell Design

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Problem Statement

The client manufactures ten different designs of diesel engine cylinder blocks and is pursuing a more productive automated solution for the task of storing, deburring and polishing the blocks. The different designs have similar shapes but are mainly different in size, differing by 10% from smallest to largest block. The blocks are cast from moulds and are then transferred to storage. *The robot cells tasks are to receive the unmachined diesel blocks from the existing storage area (starting point), transfer the blocks to a machining station, deburr and polish the engine blocks top and bottom surface at the machining station, then transfer the machined blocks to the final machined block storage area.*

Requirements of the robot cell:

- Collect the cylinder blocks from existing storage
- Recognize the model of the engine block
- Transfer the block to deburring and polishing station
- Polish the top and bottom surfaces of the engine block
- Surface debur the top and bottom surfaces of the engine block
- Edge deburr the holes on the top and bottom surfaces of the engine block
- Transfer deburred and polished engine block back to storage

Figure 1: Diesel Engine Block (Ehsan, 2020)

Production Specification:

- High run rate ~ 1000 per day
- Large storage space ~ capacity to store up to 1000 engine blocks
- Fully autonomous without human intervention
- 24/7 manufacturing facility
- Safety - fencing integrated with safety control system
- Top and bottom surfaces of engine block are flat surface with cylindrical holes
- Size of Diesel engine block 80-90cm L x 70-80cm x 70-80cm

Proposed Solutions

SubTask 1: Part Storage and Part transfer :

Subtask 1.1 Part Storage:

1. Unit Load Automated Storage Retrieval System (ASRS)
2. Racking
3. Shipping Container

Subtask 1.2 Part Transfer:

1. Intermittent Conveyor Belt
2. AGV (Automated Guided Vehicle)
3. Twisted Conveyor

SubTask 2: Part Recognition

1. RFID tags
2. 2D Machine Vision Sensor
3. 3D Machine Vision Sensor
4. Photovoltaic Proximity Sensor

SubTask 3: Flipping Mechanism

1. Turntable & Mini Conveyor Design
2. Rotating Claws Design
3. Push and Flip Design

SubTask 4: Robot

1. Scara
2. 6-axis
3. Cartesian

SubTask 5: End-Effector

1. Automatic Tool Changer Master plate with multiple tools
2. Manual tool changer
3. Automatic multi-tool end effector

Subtask 1: Part Storage and Part transfer

Subtask 1.1: Part Storage

Part Storage Selection Matrix (Score)

Solutions	Durability	Reliability	Maintenance	Efficiency	Workspace	Cost
Unit Load Automated Storage Retrieval System (ASRS)	10	9	6	9	10	2
Racking	10	9	10	1	7	7
Shipping Container	10	5	10	3	1	5

Part Storage Selection Matrix (Justification)

Solutions	Durability	Reliability	Maintenance	Efficiency	Workspace	Cost
Unit Load Automated Storage Retrieval System (ASRS)	Sufficient Strength to carry and store high load unit.	Intelligent Storage System which leads to low fault/failure probability	If product fall can damaged ASRS which leads to quite high maintenance cost	Fully automated and fast storage system. Organized Storage system	Space friendly device	Initial cost is high but will reduce production cost in long term
Racking	Durable to withstand heavy objects	Safe for Storing heavy products	Doesn't need maintenance	Require assisting automated device to store objects	Space friendly system	Initial cost is quite reasonable and reduce storage cost in long term
Shipping Container	Can store any heavy objects	Safe to store heavy load objects Stacking product on top of each other can damage product	Doesn't need maintenance	Require assisting system to transfer object to the storage.	Excessive space consumption	Initial cost is quite high but will reduce in long term

Subtask 1: Part Storage and Part transfer

Subtask 1.2: Part Transfer

Part Transfer Selection Matrix (Score)

Solutions	Strength	Reliability	Speed	Efficiency	Safety	Cost
Intermittent Conveyor belt	10	9	8	9	10	6
AGV (Automated Guided Vehicle)	10	9	8	9	10	2
Twisted Conveyor	8	3	6	5	5	5

Part Transfer Selection Matrix (Justification)

Solutions	Strength	Reliability	Speed	Efficiency	Safety	Cost
Intermittent Conveyor belt	Heavy Duty System	Feed and Transfer product to the correct system.	Fast transfer and feeding system	Automated transport system however	Safe for any workers around the system. Safe product transfer	Cost depends on the workcell.
AGV	Able to withstand 50 Kg load objects	Intelligent system that can transport and organize raw and final product Increase manufacturing flexibility	Time efficient transport system.	Enhances transport workflow Traffic Control device	Safe product transfer system Sensor on the device with only follows transport pathline that is	Initial cost is high but will reduce production cost in long term
Twisted Conveyor	Sufficient to move heavy object	Object might not be transferred correctly	Twisting transfer pathline reduce transfer rate	Twisted feed and transfer pathline is unnecessary	Doubtful transfer mechanism with respect to product's safety	Cost depends on the workcell. Quite expensive

Costing 1: Part Storage and Part transfer

Subtask 1.1 Part Storage

Solution	Price
Unit Load ASRS Automated Storage Retrieval System (ASRS)	This system is approximated to be ~$1,000,000
Racking	It is approximated to be ~$650 for 12 spaces racking
Shipping Container	- Standard 20ft container: ~$3500 - $4000 - 40ft Container: ~$6000

Subtask 1.2 Part Transfer

Solution	Price
Intermittent Conveyor Belt	~ $200 per meter
AGV	Average cost of this device is $100, 000 - $150, 000
Twisted Conveyor	It is approximated to be ~$475 per meter

Part Storage and Part transfer Recommendation

Subtask 1.1 Part Storage:

1. Unit Load ASRS is chosen as it provides a fully autonomous operation.
2. It is programmable, reliable to organize and store diesel engine blocks
3. Initial cost is high. However, it provides greater efficiency than other system and will reduce operational cost in long term.

Figure 2: ASRS Storage (Made-in-China , 2020)

Subtask 1.2 Part transfer:

1. Intermittent conveyor belt is select for the transport system.
2. Initial cost is reasonable considering features it provides.
3. Start and Stop system allows to track of how many diesel block that have been processed.

Figure 3: Intermittent/Automatic conveyor belt (AUTOMATED CONVEYOR SYSTEMS, INC. , 2020)

Subtask 2: Part Recognition

Part Recognition Selection Matrix (Score)

Solution	Integrability	Presence Detection	Position & Orientation Detection	Moving Object Geometry Detection	Model Identification Accuracy	Fault Detection	Reliability & Maintenance	Cost
RFID tags	1	10	3	0	10	0	9	1
2D Machine Vision Sensor	10	10	10	5	8	8	10	5
3D Machine Vision Sensor	10	10	10	10	10	10	10	4
Photovoltaic Proximity Sensor	10	10	5	0	5	0	10	8

Part Recognition Selection Matrix (Justification)

Solution	Integrability	Presence Detection	Position & Orientation Detection	Moving Object Geometry Detection	Model Identification Accuracy	Fault Detection	Reliability & Maintenance	Cost
RFID tags	Needs assistance to stick tags onto block	Easily detects presence	Detects block from a predefined distance from Robot	Can’t detect geometry	Can’t identify block type	Can’t detect manufacturing faults	RFID tags are reliable and don’t need maintenance	Low initial cost but ongoing cost is large
2D Machine Vision Sensor	Easy installation & calibration	Easily detects presence	2D position & orientation determination	Detects 2D geometry - may not capture all size changes	Detects model type using 2D image	Can detect faults	Reliable once calibrated, easily replaced	Large initial cost but single purchase
3D Machine Vision Sensor	Easy installation & calibration	Easily detects presence	3D position & orientation determination	Detects 3D geometry - will capture all size changes	Detects model type using 3D image	Can detect a wider range of faults	Reliable once calibrated, easily replaced	Large initial cost but single purchase
Photovoltaic Proximity Sensor	Easy installation & calibration	Easily detects presence	Detects block from a predefined distance from Robot	Can’t detect geometry	Cannot detect block type	Can’t detect faults	Reliable once calibrated, easily replaced	Low initial cost but single purchase

Costing 2: Part Recognition

Solution	Price
RFID tags	$0.50/tag + costs of machine that will apply tags to engine blocks
2D Machine Vision Sensor	$3000 vision sensors, 1 recommended for backup redundancy
3D Machine Vision Sensor	$6000 vision sensors, 1 recommended for backup redundancy
Photovoltaic Proximity Sensor	$200 per sensor plus redundancy sensors

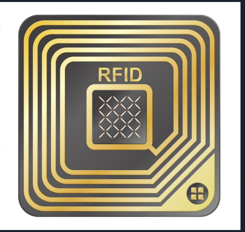


Figure 4: RFID tags (SICK Sensor Intelligence, 2020)

Figure 5: 2D Machine Vision Sensor (SICK Sensor Intelligence, 2020)

Figure 6: 3D Machine Vision Sensor (SICK Sensor Intelligence, 2020)

Figure 7: Photovoltaic Proximity Sensor(SICK Sensor Intelligence, 2020)

Part Recognition Recommendation

1. The TriSpector1000 V3T13S-MR62A7 was chosen because it is a reliable 3D line scanning inspection technology which can distinguish different designs through a high profile resolution within the field of view.
2. The user interface provides an ease of use and make commissioning and operation easy. Can be quickly replaced so low downtime costs are applicable. Can also withstand harsh environments, making it a reliable and efficient way of differentiating the 10 engine block designs and relaying that information to the other equipment in the robot cell through the control system.
3. It's cost compared to the other solutions is acceptable because it is durable, reliable and accurate which is necessary for a high scale robot cell.
4. The vision sensor for the robot cell will be located at cartesian robot to provide the cartesian robot with type confirmation and increased accuracy in deburring and polishing the different machining paths. It will also provide information to downstream equipment through the control system.

Figure 8: 3D Machine Vision Trispector1000 product range (SICK Sensor Intelligence, 2020)

Subtask 3: Flipping Mechanism (Proposed Designs)

Design 1:

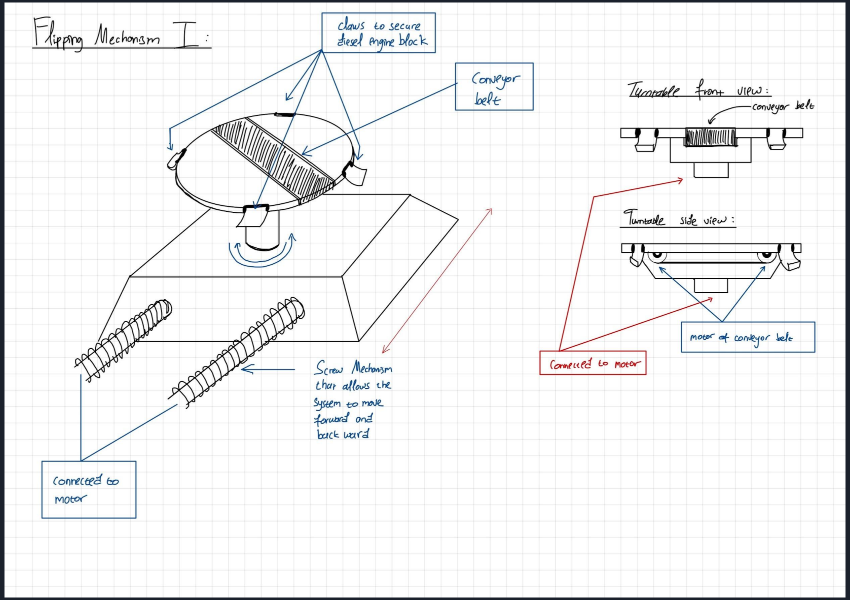


Figure 9: Turntable & Mini Conveyor Design (Group 18, 2020)

Design 2:

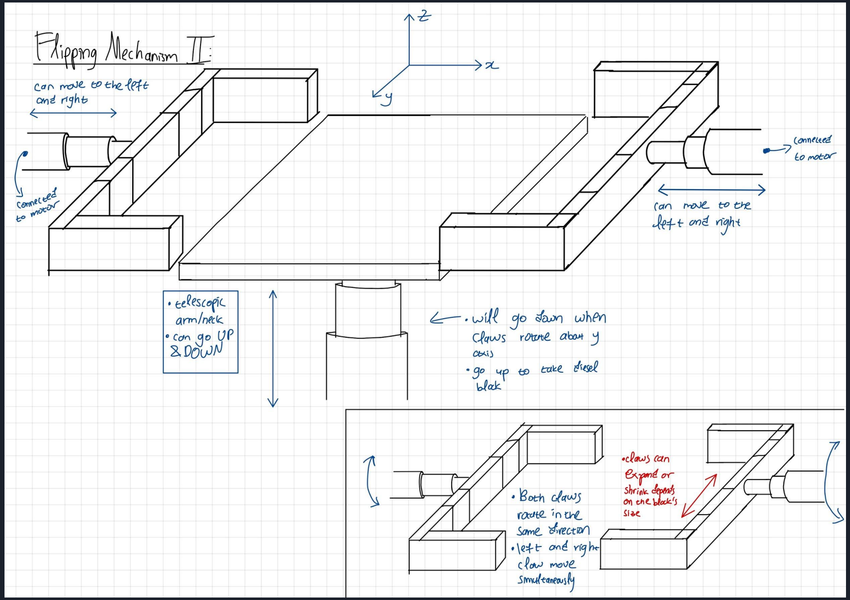


Figure 10: Rotating Claws Design (Group 18, 2020)

Subtask 3: Flipping Mechanism (Proposed Designs)

Design 3:

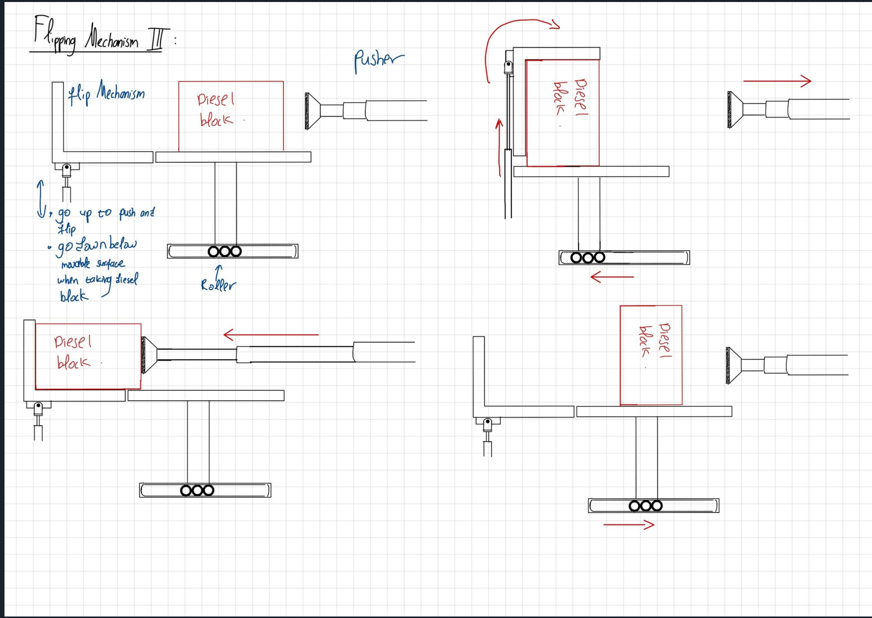


Figure 11: Push and Flip Design (Side View) (Group 18, 2020)

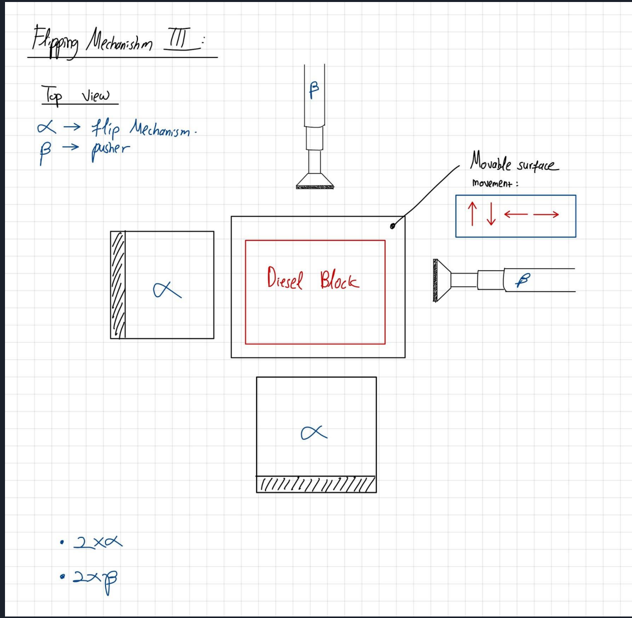


Figure 12: Push and Flip Design (Top View) (Group 18, 2020)

Subtask 3: Flipping Mechanism

Flipping Mechanism Selection Matrix (Score)

Solutions	Durability	Reliability	Time	Efficiency	Safety	Cost
Turntable & Mini Conveyor Design	10	8	10	9	9	6
Rotating Claws Design	9	9	9	8	8	3
Push and Flip Design	7	5	5	4	3	2

Flipping Mechanism Selection Matrix (Justification)

Solutions	Durability	Reliability	Time	Efficiency	Safety	Cost
Turntable & Mini Conveyor Design	Sufficient to withstand weight of a diesel engine cylinder block	Secure engine block and allows robot to execute deburring and polishing process at any angle	Time friendly flipping/rotating mechanism.	Simple design mechanism that allows the robot deburr and polish engine block without needing the robot to translate to different position	Closed space operation which won't harm workers nearby Emergency button	Reasonable cost and reduce production cost in long term.
Rotating Claws Design	Claw able to hold engine block when being flipped	Secure engine block when being flipped, and when being deburred/ polished.	Fast flipping mechanism	Fast and reliable mechanism to support deburring and polishing process. Design 2 is more complex than Design 1	Closed space operation. (Won't harm workers nearby). Emergency button	Cost will relatively higher than Design 1 but will reduce production cost in long term
Push and Flip Design	Surface can be damaged when changing orientation of the block	Position of the diesel engine is less secured	Changing Orientation of the engine block might take time	Less efficient movement to change orientation of the block	Diesel might get damaged when being rearranged.	Complex system leads to high cost but result might be unsatisfactory

Costing 3: Flipping Mechanism

Solution	Price
Turntable & Mini Conveyor Design	~ $8,000 for 1 unit
Rotating Claws Design	~ $17,000 for 1 unit
Push and Flip Design	~ $11, 000 for 1 unit.

Flipping Mechanism Recommendation

Turntable & Mini Conveyor Design is selected for the flipping system, because :

1. System is simple and provide efficient operation
2. Reasonable cost
3. Faster and allows robot to deburred and polished diesel block from required angle
4. Secured diesel block and provide support force for robot to deburred and published the product.
5. Reduces the size & payload requirement for the robot.

Subtask 4: Robot

Robot Selection Matrix (Score)

Solutions	Degree of Freedom	Workspace	Load Capacity	Speed	Repeatability and Accuracy	Kinematic Configuration
Cartesian (Includes three linear slides at right angles to each other)	5	10	10	7	9	10
Scara (Two link arm layout)	8	6	7	9	9	8
6-axis	10	9	8	5	9	8

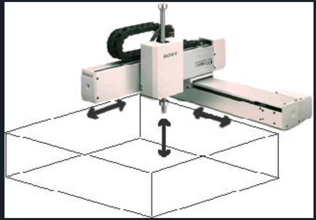


Figure 13: 3 DOF Cartesian Robot (LINEAR MOTION TIPS, 2018)

Figure 14: SCARA Robots (Allied Automation, 2020)

Figure 15: 6-axis Industrial Robot (Samuel, 2016)

Robot Selection Matrix (Justification)

Solutions	Degree of Freedom	Workspace	Load Capacity	Speed	Repeatability and Accuracy	Kinematic Configuration	Limitations
Cartesian (Includes three linear slides at right angles to each other)	3 Translations	Large workspace	Can handle large load	Average speed	Rigidity and precision results in very good repeatability	3 linear slides at right angles to each other. Very easy to program	Limited tool orientations Requires a large amount of space.
Scara (Two link arm layout)	3 Translations 1 Orientation	Limited workspace	Average load capacity	Very fast	Very precise and rigid, good repeatability	Ideal for circular motion applications	Poor vertical plane manipulation
6-axis	3 Translations 3 Orientations	Large workspace	Large load capacity	Quite slow	High repeatability and accuracy	Very versatile. Allows for multiple orientations.	Slow

Costing 4: Robot (Matt)

Solutions	Costs
Cartesian	Linear motors, standardised components and operator friendly controls allows for lower cost ~$50,000
Scara	Complex design and controls increase cost ~$70,000
6-axis	Complex design and controls increase cost ~$70,000

Chosen Robot - Yamaha FXYx

Model	Axes	Maximum Payload	X-axis Stroke	Y-axis Stroke
Yamaha FXYx	3 Axes	12kg	150 - 1050 mm	150-550

Figure 16: Yamaha FXYx Cartesian Robot (Yamaha Motor)

Robot Recommendation

1. A cartesian robot was chosen because it is cheaper and more relevant to the task.
2. Given that the flipping is being done by the turntable, the majority of motion needed by the robot arm is left and right to cover the engine surface. This favours the linear motion of a cartesian robot.
3. The Yamaha FXYx model was chosen due to its reach and payload, given that the only load on the robot arm will be the tool changing mechanism and the deburring and polishing tools.

Subtask 5: End-Effector

End-Effector Selection Matrix (Score & Justification)

Solutions	Speed	Cost
Automatic Tool Changer Master plate with multiple tools	6 - No manual intervention required, but still requires the robot arm to go back and forth between the workspace and the tool storage	8 - Reasonably high cost, but requires little to no ongoing costs
Manual Tool Changer	2 - Very slow, as it requires human intervention for each tool change	4 - Low initial cost, but high ongoing costs due to manual labour
Automatic multi-tool end effector	10 - Very fast, arm just needs to rotate position to change tool	2 - Very expensive, but requires little to no ongoing costs

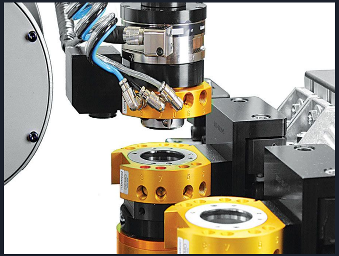


Figure 17: Automatic Tool Changer (Destaco, 2015)

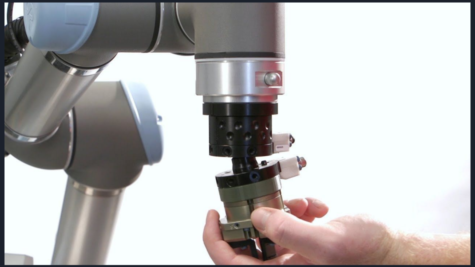


Figure 18: Manual Tools Changer (ATI Industrial Automation, 2018)

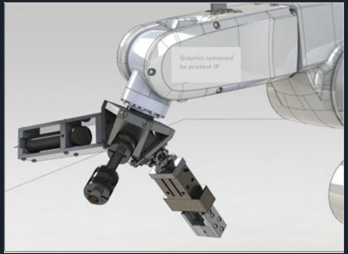


Figure 19: Automatic multi-tool end effector (Killol)

Subtask 5: End-Effector (Tools required)

<u>Tools Required:</u>

1. Surface deburring tool
2. Edge deburring tool/chamfer for holes
3. Surface polisher

Tools will contain radial compliance which allows for small errors in block orientation. This means that the robot arm does not need an orientation axis.

For example, if the engine block is a few degrees off parallel with the robot arm, the tool itself will rotate so that the end of the tool is parallel with the surface being worked on.

<u>Figure 20:</u> Tools required at the end-effector (ATI Industrial Automation, 2020)

Costing 5: End-Effector

Solutions	Cost
Automatic Tool Changer Master plate with multiple tools	~$8000 including three tool end effectors
Manual Tool Changer	~$5000 including three tool end effectors (plus ongoing labour costs)
Automatic multi-tool end effector	~$10000

End-Effector Recommendation

1. The Automatic Tool Changer with master plate and multiple tools was chosen for this application due to its many advantages. It allows the robot to change tools automatically without human intervention and therefore allows for the process to run 24/7.
2. While the multi-tool end effector includes these same benefits with increased speed of tool changing, the benefits do not outweigh the cost. The larger weight of this end effector would also increase the required payload of the robot and hence increase the robot costs further also.

Preliminary Costing

Solution	Cost
Subtask 1.1: Part Storage	
Unit Load ASRS Automated Storage Retrieval System (ASRS)	~$1,000,000
Subtask 1.2: Part Transfer	
Intermittent Conveyor Belt	~$200 per meter X 13 meters in total = ~$2,600
Subtask 2: Part Recognition	
3D Machine Vision Sensor	~$6000
Subtask 3: Flipping Mechanism	
Turntable & Mini Conveyor Design	~$8,000 per 1 unit
Subtask 4: Robot	
3 DOF Cartesian Robot	~$50,000
Subtask 5: End Effector	
Automatic Tool Changer - Master Plate with Multiple Tools	~$8,000
Total Cost : ~$1,074,600	

Final Recommendation

It is proposed that the robot cell be composed of the following equipment for each subtask:

<u>SubTask 1: Part Storage and Part transfer</u>

- Subtask 1.1: Part Storage → Unit Load Automated Storage Retrieval System (ASRS)
- Subtask 1.2: Part Transfer → Intermittent Conveyor Belt

<u>SubTask 2: Part Recognition</u> → TriSpector1000 V3T13S-MR62A7 3D Machine Vision Sensor

<u>SubTask 3: Flipping Mechanism</u> → Turntable & Mini Conveyor Design

<u>SubTask 4: Robot</u>→Yamaha FXYx 3-axis Cartesian Robot

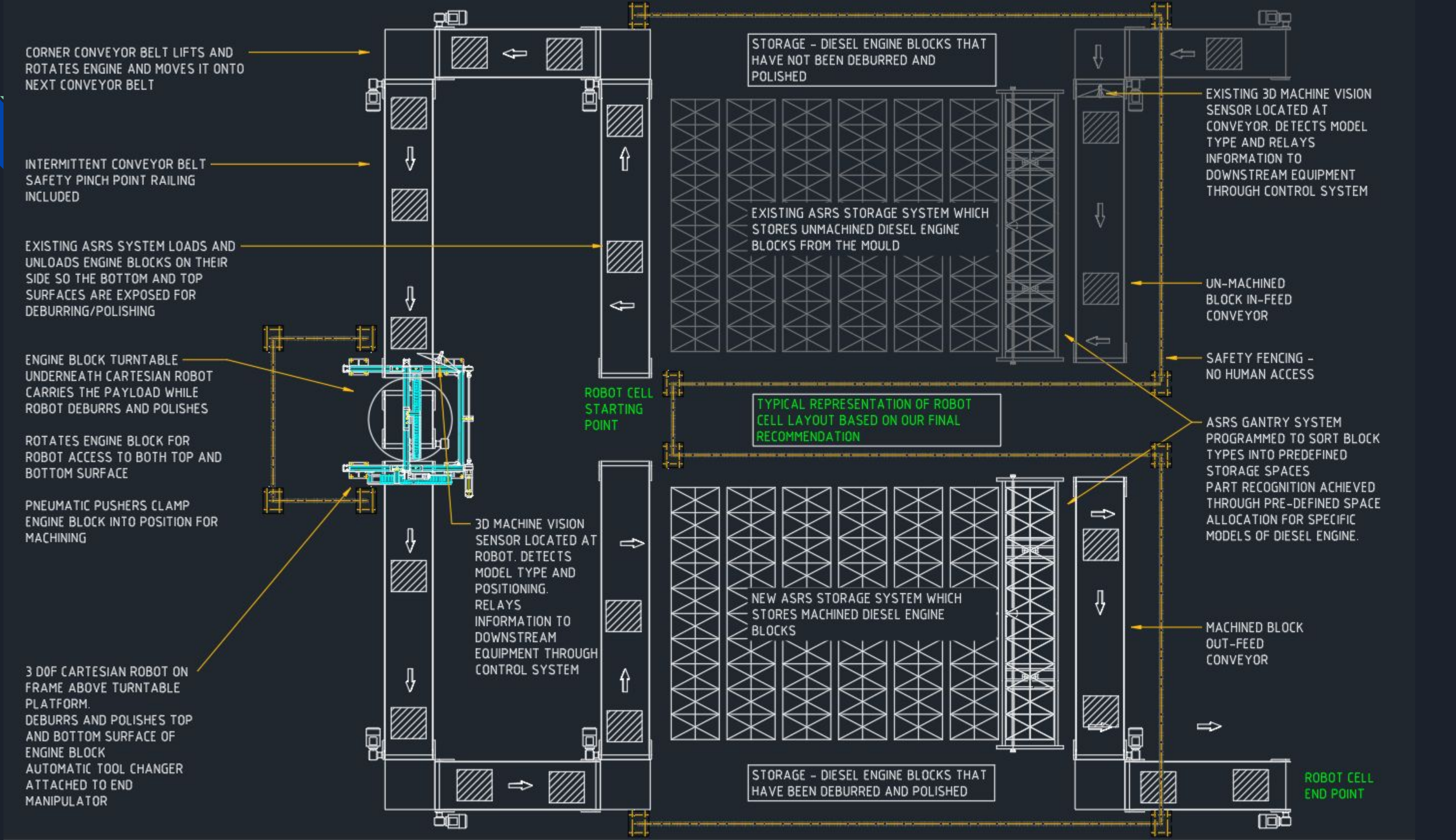
<u>SubTask 5: End-Effector</u>→ Automatic Tool Changer with master plate and three tool end effectors (Surface deburring tool, edge deburring tool, surface polishing tool)

Safety considerations

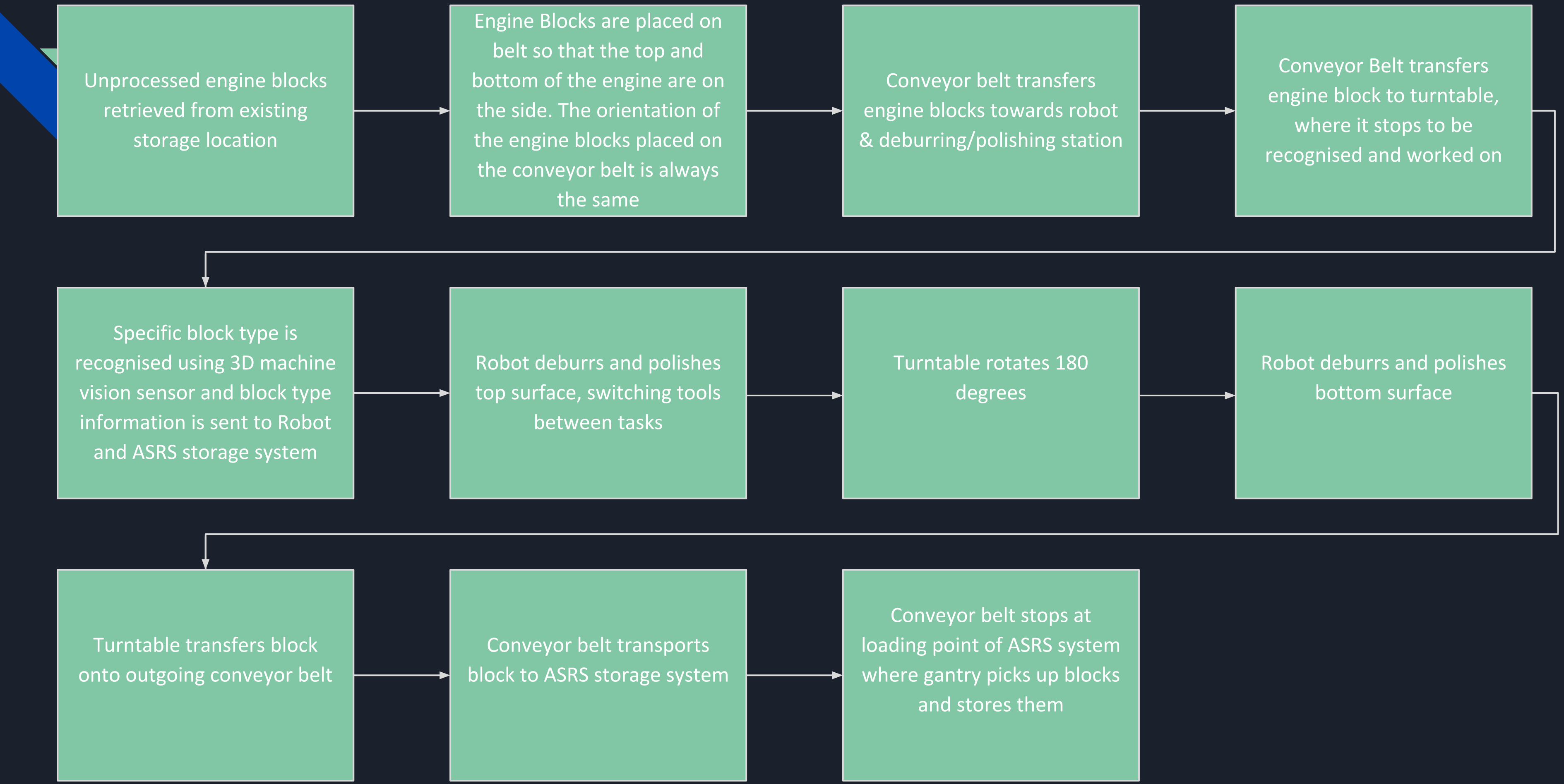
1. Safety fences to be incorporated - System is completely surrounded by safety fences
2. Safety hinge switch - Automatic system switch off when fence gates are opened
3. Dead man switch, when manually operating system - Automatic system shut off when hands come off switch or double press switch
4. Emergency stop buttons surrounding system in case of emergencies
5. Circuit breaker in case of electrical faults

Figure 21: Typical machine and automation safety features (Teksal Safety, 2020)

Workcell Schematic Diagram


CORNER CONVEYOR BELT LIFTS AND ROTATES ENGINE AND MOVES IT ONTO NEXT CONVEYOR BELT
INTERMITTENT CONVEYOR BELT SAFETY PINCH POINT RAILING INCLUDED
EXISTING ASRS SYSTEM LOADS AND UNLOADS ENGINE BLOCKS ON THEIR SIDE SO THE BOTTOM AND TOP SURFACES ARE EXPOSED FOR DEBURRING/POLISHING
ENGINE BLOCK TURNTABLE UNDERNEATH CARTESIAN ROBOT CARRIES THE PAYLOAD WHILE ROBOT DEBURRS AND POLISHES
ROTATES ENGINE BLOCK FOR ROBOT ACCESS TO BOTH TOP AND BOTTOM SURFACE
PNEUMATIC PUSHERS CLAMP ENGINE BLOCK INTO POSITION FOR MACHINING
3 DOF CARTESIAN ROBOT ON FRAME ABOVE TURNTABLE PLATFORM.
DEBURRS AND POLISHES TOP AND BOTTOM SURFACE OF ENGINE BLOCK
AUTOMATIC TOOL CHANGER ATTACHED TO END MANIPULATOR
ROBOT CELL STARTING POINT
3D MACHINE VISION SENSOR LOCATED AT ROBOT. DETECTS MODEL TYPE AND POSITIONING.
RELAYS INFORMATION TO DOWNSTREAM EQUIPMENT THROUGH CONTROL SYSTEM
STORAGE - DIESEL ENGINE BLOCKS THAT HAVE NOT BEEN DEBURRED AND POLISHED
EXISTING ASRS STORAGE SYSTEM WHICH STORES UNMACHINED DIESEL ENGINE BLOCKS FROM THE MOULD
TYPICAL REPRESENTATION OF ROBOT CELL LAYOUT BASED ON OUR FINAL RECOMMENDATION
NEW ASRS STORAGE SYSTEM WHICH STORES MACHINED DIESEL ENGINE BLOCKS
STORAGE - DIESEL ENGINE BLOCKS THAT HAVE BEEN DEBURRED AND POLISHED
EXISTING 3D MACHINE VISION SENSOR LOCATED AT CONVEYOR. DETECTS MODEL TYPE AND RELAYS INFORMATION TO DOWNSTREAM EQUIPMENT THROUGH CONTROL SYSTEM
UN-MACHINED BLOCK IN-FEED CONVEYOR
SAFETY FENCING - NO HUMAN ACCESS
ASRS GANTRY SYSTEM PROGRAMMED TO SORT BLOCK TYPES INTO PREDEFINED STORAGE SPACES
PART RECOGNITION ACHIEVED THROUGH PRE-DEFINED SPACE ALLOCATION FOR SPECIFIC MODELS OF DIESEL ENGINE.
MACHINED BLOCK OUT-FEED CONVEYOR
ROBOT CELL END POINT

Workcell Block Diagram


Unprocessed engine blocks retrieved from existing storage location
Engine Blocks are placed on belt so that the top and bottom of the engine are on the side. The orientation of the engine blocks placed on the conveyor belt is always the same
Conveyor belt transfers engine blocks towards robot & deburring/polishing station
Conveyor Belt transfers engine block to turntable, where it stops to be recognised and worked on
Specific block type is recognised using 3D machine vision sensor and block type information is sent to Robot and ASRS storage system
Robot deburrs and polishes top surface, switching tools between tasks
Turntable rotates 180 degrees
Robot deburrs and polishes bottom surface
Turntable transfers block onto outgoing conveyor belt
Conveyor belt transports block to ASRS storage system
Conveyor belt stops at loading point of ASRS system where gantry picks up blocks and stores them

Literature Reviews

Journal Lists

Journal Review Part 1:

a. Collaborative Assembly in Hybrid Manufacturing Cells: An Integrated Framework for Human–Robot Interaction

b. Human–Robot Collaboration in Manufacturing Applications: A Review

Journal Review Part 2:

a. Symbiotic human–robot collaborative approach for increased productivity and enhanced safety in the aerospace manufacturing industry

b. Sensor-less external force detection for industrial manipulators to facilitate physical human-robot interaction

Journal Review Part 3:

a. Triple stereo vision system for safety monitoring of human-robot collaboration in cellular manufacturing

b. Optimization of Temporal Dynamics for Adaptive Human-Robot Interaction in Assembly Manufacturing

Journal Review Part 1

Journal 1: Collaborative Assembly in Hybrid Manufacturing Cells: An Integrated Framework for Human–Robot Interaction

**Note - *<u>pHRI:</u>* *Physical Human Robot Interaction;* *<u>sHRI:</u>* *Social Human Robot Interaction*

- **<u>Problem:</u>** Physical performance of human workers vary on his/her interaction, physical strength and working pattern with robot.
- **<u>Proposed Solutions:</u>** Offering robot motion controller in order to meet human physical demands, adapting to the progress of human motion. This will enhances human's trust to robot, avoid collision and minimize human workload.
- **<u>Result of Proposed Solutions:</u>** The result of the offered solution shows that by utilizing autonomous sHRI and pHRI controller are far superior than manually adjust robot velocity to maintain human work pace. Autonomous sHRI and pHRI maintain the overall performance of human-robot team collaboration while minimizing human workload. The solution shows that autonomous sHRI build human's trust to robot and enhanced pHRI. Robot Facial expressions provide feedbacks for safety concerns and manufacturing performance. Hence, increase robot usability.

Journal Review Part 1

Journal 2: Human–Robot Collaboration in Manufacturing Applications: A Review

**Note* - cobots: Collaborative Robots; SME: Small and Medium sized Enterprises*

- **Problem:** Collecting information/knowledge for the correct use and characteristics of cobots is still become a barrier for an industry for them so utilize cobots to its full potential.
- **Proposed Solutions:** Creating an overview that shows the current standards human robot collaboration can be utilize in wide range with variety of modes. Executing literature analysis of 41 papers and 35 industrial case studies which focused on human robot collaboration, control system and methodologies of collaboration.
- **Result of Proposed Solutions:** As cobots become cheaper and easier to be operated in a workcells, it is expected that SME from large range of industrial applications use this technology compare to electronic and autonomous system.

Journal Review Part 2

Journal 3: Symbiotic human–robot collaborative approach for increased productivity and enhanced safety in the aerospace manufacturing industry

- **Problem:** Enabling robots to actively comply to human intentions through task adaptation is necessary for safe human - robot collaboration.
- **Proposed Solutions:** Development of an impedance controller that allows for force level compliance and more than one dynamical system to define the tasks known to the robot.
- **Result of Proposed Solutions:** Having several dynamical systems allowed for smooth human-robot interaction, creating a safer environment for human operators.

Journal Review Part 2

Journal 4: Sensor-less external force detection for industrial manipulators to facilitate physical human-robot interaction

- **Problem:** Although industrial robots are equipped with actuator current/torque sensors in the robot joints, the actuator torque sensors themselves are not enough to detect external force because they are affected by the inertia and friction of the robot and external force at the same time.
- **Proposed Solutions:** The dynamic models of the robot in both dynamic mode and quasi-static mode were used to characterize the behaviour of the robot instead of current/torque sensors.
- **Result of Proposed Solutions:** Dynamic models have the capability to detect external force on industrial robots without prior knowledge of the external force and doing no harm to the mechanical structure of the robot

Journal Review Part 3

Journal 5: Triple stereo vision system for safety monitoring of human-robot collaboration in cellular manufacturing

- **Problem:** Close range collaboration between human and robot using same workspace can cause safety issues. Using the same workspace means that physical barriers or light curtains cannot be used.
- **Proposed Solutions:** Stereo vision system to detect human movement. Human operators wear a colour coded uniform to allow easier tracking of movement by the cameras. Two or three cameras are used to retrieve the human's positions in 3D space.
- **Result of Proposed Solutions:** Two cameras resulted in lost tracking, which resulted in moments where the system was temporarily 'blind' to the movements of the human. Adding the third camera improved the robustness significantly, however still requires further work.

Journal Review Part 3

Journal 6: Optimization of Temporal Dynamics for Adaptive Human-Robot Interaction in Assembly Manufacturing

- **Problem:** Human interaction means that task priorities and timings may change, which can affect production line flow.
- **Proposed Solutions:** Adaptive Preferences Algorithm (APA). Uses a non-linear program solver to program a flexible scheduling policy that is optimal to the application. It allows for real-time optimisation adjustments in response to changing preferences caused by human interaction.
- **Result of Proposed Solutions:** APA provides significant robustness to human input disturbances, and it can accurately schedule 20 tasks adaptively with sub-second speed. Trials showed that a robot using this system was able to adjust its timing and scheduling based on different users and situations. Future work includes increasing the number of tasks to schedule, as well as scaling up to multi-robot orchestration problems.

Journals Overall Review

Main Problem 1:

Collaborative robots are required to be able to comply and detect human intentions as well as adapt to a human's motions and strength.

Possible Solutions:

- Adapting task preferences and timings in real-time.
- Having several dynamic systems to expand the options the robot has when collaborating with a human

Main Problem 2:

Collaborative robots are also required to recognise when a movement may be unsafe for a human and change its motion to avoid collisions. During a collision, a robot needs to minimise external forces on a human.

Possible Solutions:

- Creating system that provide feedbacks to the collaborator to maintain work safety and consistency.
- Stereo vision system to recognise human movements

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