A Novel Passive Grasping Robot Control Framework Towards Vision-Based Industrial Steel Bar Conveyor Removal

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Abstract

Material handling using robotic automation is critical for enabling efficient and safe environments for numerous industries. In the steel bar manufacturing industry bars of shorter length are occasionally produced that do not match the required batch length. Currently human operators visually classify and manually remove the short bar from a batch of rods moving on a conveyor. This can present a manual handling health and safety risk. This paper demonstrates the output of a feasibility study investigating this problem; resulting in a novel, passive grasping robotic control framework that: (a) emulates the human operator's technique; and (b) successfully removes multiple bar types from a moving conveyor using closed-loop visual control.

Figure 1: An operator picking up a short bar from the moving conveyor and flicking it into the Removal Bay.

1 Introduction

Fully vertically-integrated steel manufacturers (such as InfraBuild) recycle, manufacture, and distribute long steel products for the building and civil engineering industry. Certain manufacturers often are required to utilise the same production line to fabricate several products due to the market they exist within. This multi-use production line requires alterations to the configuration reducing the ability to use standard automation procedures due to financial feasibility. The result is the use of human operators (Figure 1), creating potential risk scenarios in the case of equipment failure, no matter the mitigation strategies. Therefore, an opportunity exists to utilise advanced automation techniques (ideally collaborative robot arms) to improve the safety and efficiency for these manufacturers while not impacting on the reconfigurability of their multi-use production lines. In this paper we investigate a vision-based passive grasping robot control framework for three (3) bar section products, specifically: a 12 mm rebar, a 20 mm round bar, and a 10 mm square bar. We will refer to these simply as 12 mm, 20 mm, and 10 mm bars for the remainder of this paper. Although we used an industrial scale robot arm for the experiments described in this paper, the research was undertaken with the knowledge that a collaborative robot arm is the target robot for the final installed solution, based on the fact that a human operator currently performs the task easily using only one arm.

The manufacturing procedure can result in the creation of a bar that is marginally shorter in length than the rest in a batch. A 'short' bar in such production lines is not unheard of; a French Technical Bulletin from 1967 [Section, 1967] presented their own method of 'short' bar removal via an automated process. Although this presented an interesting solution, it is tailored to the commercial bar length suitable – an ever changing outcome depending on the client's specifications (i.e., the length of an acceptable bar can change). Furthermore, the requirement of large changes to infrastructure should be restricted as much as possible. InfraBuild, our industry partner, conducts manual short bar removal, where the following steps are generally followed: (i) an operator awaits the next batch of bars; (ii) the operator visually identifies if the cut of the next batch results in a short bar; and (iii) if present, the operator (while wearing the appropriate Personal Protective Equipment (PPE)) removes the bar from the moving conveyor and into a bay that is located on the ground next to the conveyor. It should be noted that these steel bars are quite flexible and it is this flexibility that the human operator uses to their advantage to pick up one end of the bar and flick it off the conveyor.

Given the manual methodology, there are a number of safety considerations for the human operator to consider, including: (a) the speed of the moving bars (approx. $1\,\mathrm{m\,s^{-1}}$); (b) the relatively high temperature of the bars (approx. $100\,^{\circ}\mathrm{C}$); (c) the potential of a collision between previous and new batches along the conveyor; and (d) injury as a result of performing the prescribed action with bars of considerable length (up to 18 m). It is clear that an effective methodology be explored such that productivity and the safety of operators is enforced.

This paper: (a) reviews related work and outlines the problem definition in Sections 2 and 3; (b) details the custom *passive* gripper development and vision-based robotic control framework in Sections 4 and 5; (d) presents the overall system functionality in Section 6; and (f) concludes with a performance discussion, and remaining gaps for future work in Sections 7 and 8.

2 Related Work

A study focused on automated steel rod extraction [Gerald *et al.*, 2004] identified that it is a *well known problem in the steel industry*; however, the *problem* can vary as demonstrated in their study, where: (i) it involved the separation of steel rods from a bundle under static conditions, rather than in motion from a conveyor; and (ii) required large infrastructure (a gantry robot, a separate lift table and conveyor system, and two separate end-effectors). From this study it is clear that the most critical device on a robotic system is the end-effector, which in some cases can be tightly integrated to be an engineered *sub-system* [Jenkins, 2018]. It is also the most challenging component to design for given it is *essential* that the end-effector *relate to its specific application.*

Several studies demonstrate this case: (a) a study by [Kumar *et al.*, 2017] required a custom end-effector design for the fabrication of steel wire meshes for concrete reinforcement; (b) a study by [Ma *et al.*, 2018] tailored their end-effector design as a mini manipulator on the end of their larger (macro) manipulator, wholly to ensure high degrees of control over position and force towards industrial finishing – tasks that require constant contact between the end-effector and the work-piece; or (c) a study by [Firth *et al.*, 2022] that attempted an anthropomorphic soft robotic design to emulate the human hand, not only because the target application was to grasp construction tools, but also to reduce the potential high cost of requiring multiple end-effectors through the use of one, highly tailored, solution.

There are, of course, numerous *standardised types* of end-effector designs that can be considered at a fundamental level [Reddy and Suresh, 2013] [Jenkins, 2018] to aide in the custom design. *Mechanical grippers*, for example, are end-effectors that consist of mechanical fingers (or jaws) that are actuated by a mechanism to grasp an object. The most common type is the *parallel* gripper, which involves two (or more) opposing parallel jaws moving towards or away from each other [Jenkins, 2018] [Singh[1] *et al.*, 2022]. These grippers are commonly available as Commercial Off The Shelf (COTS) products, where their application is fairly generalised. However, some studies demonstrate how a unique design can be applied to these types of grippers, such as: (i) a study by [Yoshimi *et al.*, 2012], whose parallel gripper included two (2) soft jaws with a designed 'hook' on one to allow for the pickup of thin, flat objects off a table top – such as paper, or plastic cards; or (ii) a unique study by [Kelly-Boxall *et al.*, 2018] that incorporated two (2) different variants of grippers (a parallel *and* a vacuum type – typically utilised for relatively flat objects with smooth surfaces) as redundancy in their application of pick-and-place with challenging house-hold objects. The design won the Amazon Robotics Challenge in 2017, and showcases a multi-modal implementation utilising the fundamental design concepts.

Electro-magnetic grippers are targeted at manipulating ferrous work-pieces and are typically quite easy to control and fast to achieve adhesion to a ferrous part [Reddy and Suresh, 2013] [Singh[1] *et al.*, 2022] [Naeem *et al.*, 2021]. However, the requirement of a DC power source and an appropriate controlling unit can have its limitations: (i) namely that these systems can be quite heavy, limiting their use-case for lower payload collaborative robot arms[Jenkins, 2018]; or (ii) cases where the magnetic grasp of the work-piece may capture multiple objects. This type of gripper resonates with the objectives of this study – specifically when we consider that the study by [Gerald *et al.*, 2004] implemented an electro-magnetic gripper in their steel rod separating solution, noting that the use of this gripper there was purely as an *initial engagement of the bundle.* They required a second gripper (parallel, in this case) to extract a single rod into the next part of their process.

Due to the variety of gripper designs applicable, there are varying levels of power requirements as well. The typical power sources are: (a) electrical; (b) pneumatic; (c) vacuum, or (d) hydraulic, which are all examples of *active* actuation – i.e., requiring power [Jenkins, 2018]. The added cost associated with requiring *in-situ* power, including the added weight from such integration, could be considered a limitation given the specific scenario and the final implementation – e.g., the eventual robotic payload restrictions, or the *in-situ* power availability [Singh[1] *et al.*, 2022]. Passive grippers have two main advantages over active grippers in robotics [Crooks *et al.*, 2017]: (i) passive grippers minimise the overall power consumption, and are vital in power-limited environments; and (ii) as they do not require power to sustain a grip, energy is subsequently saved to prolong the life of the gripper, and, importantly, incorporates a built-in fail-safe in the event of a power loss. There are, of course, limitations to consider: they can be more complex mechanically to compensate for a powerless implementation, and cannot provide feedback (e.g., force sensing) to the controller. Given such limitations, it is interesting to see the advantages being successfully adapted in such studies as: (a) [Crooks *et al.*, 2017], whose goal was the design of a bio-inspired soft robotic gripper that would emulate the capability of the *tobacco hornworm* – a passive approach that causes the mechanical gripper to remain engaged with the work-piece resulting in an overall energy minimisation: albeit with active power requirements to open and close; and (b) [Carlisle *et al.*, 1994], whose overall goal was to introduce a *passive* Degrees of Freedom (DoF) to their 5-DoF robot; resulting in a reduction of cost and weight overall.

The sensing on-board the robot – in this case, with respect to its end-effector – presented a critical step in order to: (a) first detect and verify the correct bar to be picked-up; and (b) provide closed-loop feedback with respect to the robot arm end-effector control towards engaging and extracting the target bar. Multiple studies, such as [Carlisle *et al.*, 1994] [Gerald *et al.*, 2004] [Luo and Liao, 2017] and [Naeem *et al.*, 2021], present successful implementations of vision-based pick-and-place industrial systems for production line use-cases – some, notably, being successfully commissioned onsite. In fact, it is readily stipulated that a distinct grasping method under visual control is an essential solution for conveyor-line problems [Luo and Liao, 2017]. To that effect, vision-based sensing was considered for this exploration phase, with additional qualities being: (a) a light-weight sensing modality with Infrared (IR), colour, and depth information that is readily available and purchased for quick development; and (b) vision-based sensor software can be quickly deployed for maximum research time.

3 Problem Definition

From the literature, it is evident that the end-effector design is crucial and must be adequately tailored to the task at hand. While a commercial gripper could be bought, the expense to acquire and subsequently integrate and modify made this avenue infeasible to pursue. An interesting notion highlighted in [Carlisle *et al.*, 1994] was a design philosophy tailored to, at a high-level, *relate to how a dexterous human hand might approach the same problem*. While directly emulating a human hand is a viable path to pursue, evaluating how the human operator currently accomplishes the task can provide a pivotal backbone to the design. In this study, we present a prototype *passive* extraction methodology that included the following: (a) the ability to successfully remove all three bar types; (b) incorporation of interchangeability into the design – meaning the gripper includes simple mechanisms to replace the part; (c) incorporation of repeatability in the gripper action for quick testing and minimal manual resetting; (d) incorporation of a robot process flow that is not dissimilar to how the existing human operator completes the task; and (e) demonstrated closed-loop vision-based control towards passive bar extraction on a moving conveyor.

The following assumptions/restrictions were adhered to during this initial phase of work:

- A mechanism exists to provide information to the robotic system specifying if a short bar exists and where it is within a batch[1].
- The bars are expected to come parallel to each other with no overlap, however, lateral motion can occur, bunching together the bars.
- The location of the robot and its type is not critical to ensure flexibility in onsite implementation.
- The conveyor speed for the test setup had an approx. maximum of $30\,\mathrm{cm\,s^{-1}}$ due to safety reasons.
- The longest bar length considered was approx. 6 m (half the conveyor length). This was for safety reasons due to the location of the testing setup.

4 Gripper Design – a Tine

A flexible, interchangeable, and quick to manufacture gripper design was desired for this study. The reasoning for this included: (a) the ability to easily change the gripper type if a design could not accommodate the various bar types (mainly if further studies are performed with an increased number of bar types); and (b) unknowns as to the optimal gripper design. It was also a primary aim to design a passive gripper to not only reduce manufacturing and operating complexity, but to gain benefits such as reduced power requirements and inherent fail-safe conditions with respect to grasping (Section 2). For this study, we opted for a design approach that was based on observation and affect. This was chosen over a principled design approach (e.g., simulation, mathematical

[1] The 'short' bar classification problem was investigated as part of this project. However, it is not discussed within this paper as the primary focus is on the key outcomes of the robotic implementation (control) of the passive gripper.

Figure 2: The gripper is a tine that hooks under a bar and lifts it. The tine moves down next to the bar being lifted (left), rotates beneath the bar (middle), and then lifts to softly engage the bar(right).

modelling, and finite element analysis) due to the experimental and fast-paced nature of the project. However, safety was at the forefront of our design choices.

The gripper design *foci* in combination with the manufacturing equipment on-hand (3D printers, wood laser cutters, and small-sized water jet cutters) lead to the following tine-like design, (Figure 3). The base assembly consisted of four (4) parts, which were: (a) the base plate; (b) two identical locking plates; and (c) the tine. The base and locking plates were symmetrical and could be attached inline or orthogonal to the robot wrist.

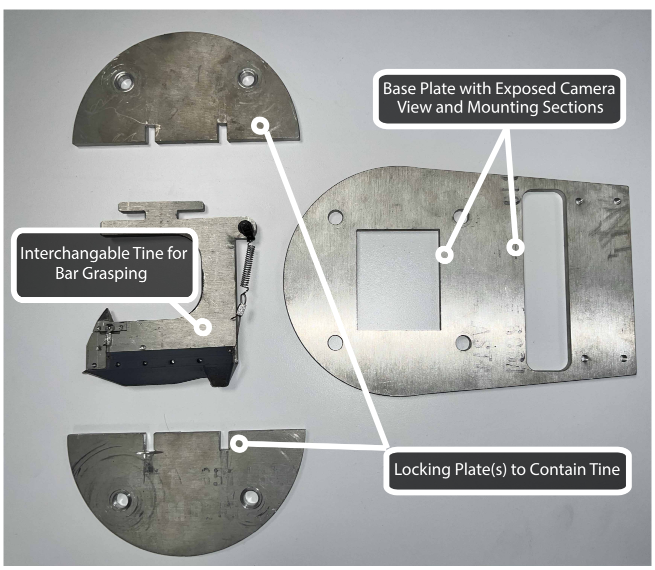

Figure 3: Illustrated is the gripper base assembly, comprising: (a) a base plate for mounting the camera and the tine; (b) two locking plates; and (c) the tine itself. Note that the final version of the tine is pictured.

4.1 Tine Design Improvements

Through rapid prototyping and evaluation of the system components, with emphasis on the tine, a solution was reached with a large quantity of design improvements. Using low cost manufacturing, models were produced to confirm fit and actuation, followed by the production of key structural components from Computerized Numerical Control (CNC) water jet cut aluminium for each design iteration. This functional model was then evaluated under representative operating conditions to validate the current operational phase's methodology and to inform the next iteration's improvement. Figure 4 presents a capture of the five (5) major designs created, composed of eight (8) design modifications/improvements. All design iterations were symbiotically tailored to the final robot control behaviours implemented (see Section 6). A summary of key design improvements are:

- Removal of a redundant vertical fin, and the inclusion of internal radii to increase stiffness of the tine;
- addition of a gated tooth (transmission of force via a machined shaft along the horizontal edge) for *passive* grasp and release of the target bar;
- vertical member thickness increase to combat bending of the tine, with base fin improvements: (a) to move the leading point of engagement directly below the vertical member, rather than at an offset; and (b) the inclusion of a protruding wedge for faster separation of the bars; and
- redesign of the gated hinge to a cabled mechanism via a common pin butt hinge, removing the need for a custom turned shaft.

4.2 Final Design

The final design prototype – as pictured in Figure 4 – maintained its 'G-shaped' design, with a mixture of ad-

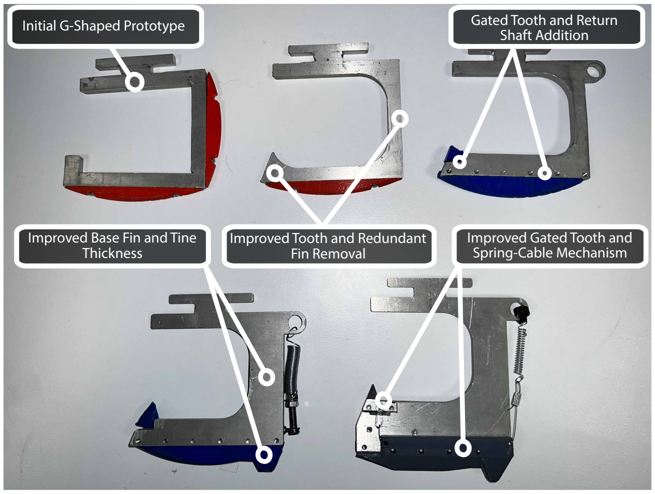

Figure 4: The five (5) design prototypes made consisting of eight (8) major design improvements. Note the first 'G-shaped' tine design (top left) and the final passive, gated tooth design (bottom right).

ditive manufactured plastic parts and water jet cut aluminium. *Passive* actuation – as highlighted in Section 2 – was the end goal. The gate provides this passive ability to: (a) lock when engaging a bar from one direction; and (b) releasing engagement with the target bar from the opposite direction, making the robotic implementation trivial with respect to the motion required to engage and subsequently disengage the target bar into a removal bay. The updated cabling to control the gated actuation presented a *self-resetting* capability to the design, which incorporated repeatability in the designed part that significantly aided in testing. The internal geometry of the tine hook, provided accommodation for handling multiple bar types – specifically the bar types within scope – with a *generic* grasping methodology to lock against bar types of varying diameter/widths. Finally, the use of two (2) wedges: (i) one protruding from the base of the tine; and (ii) the other integrated into the profile of the tooth, enabled the challenging separation of a target bar from adjacent bars.

As is the nature of prototyping, there are limitations with this final iteration that needs to be considered in future work. While additive manufacturing aided in rapid development, the PLA plastic would need to be replaced with a more appropriate material or different manufacturing technique would need to be utilised. The gated mechanism, while functional, lacks tight integration into the tine structure. Furthermore, the serviceability of the hinge and cable mechanism requires large disassembly of the part. Better integration of the pivoting return mechanism could allow for ongoing servicing and, additionally, protection of key components – particularly during the separation of the bars. Finally, given the nature of the action, lots of wear areas (where contact is made with steel) needs further consideration. These areas could be reinforced with easily replaceable, cost-effective sacrificial plates.

5 Robot Implementation

The robot used for this study was the ABB IRB6700 (Figure 5). This robot arm has a designation of IRB6700-200/2.60, which means it has a large handling capacity of approx. 200 kg with a max reach of 2.60 m^2. This study also utilised a Force Torque Sensor to suit the IRB6700-200/2.60. This sensor could handle upwards of 6250 N in the z axis, with maximum limitations of 2500 N in the x and y axes. Given the capabilities of the ABB robot, the platform presented a valuable asset to assess the feasibility of the solution. The goal of the project is to develop a solution based on a collaborative robot with a payload capability similar to a single human arm. The ABB was used for this first stage of the project out of convenience and to allow a more rapid development path given its maximum reach.

5.1 Software Framework

Most robotic platforms have their own interfaces, primarily designed for human-operator usage directly through either a proprietary teach pendant, or via an external means. The ABB has its own programming language called 'RAPID' to declare variables of different data types, and program in fundamental logic operations. RAPID, in addition to its base functionality, provides functions that govern: (a) external input/output to the robot controller; and (b) the force torque data extraction – the two components used to enable data communication between the robot controller and Robot Operating System (ROS). External input and output is performed through a RAPID application called Externally Guided Motion (EGM) that utilises their EGM Position Guidance method – this provided a low-level interface to the robot controller to read/write positions to the motion system every 4 ms.

The open-source *abb_robot_driver*[3] ROS package from *ros-industrial*[4] included ready to run ros_control nodes that linked to the EGM and Robot Web Services (RWS) C++ libraries provided by ABB. The ros_control packages are a generic framework for implementing common interfaces between hardware (i.e., the robot) and ROS. The QUT Centre for Robotics (QCR) developed the ARMer driver[5] – a ROS-based high-level hybrid controller for robotic manipulators. While traditional con-

[2] ABB Product Specification.
[3] https://github.com/ros-industrial/abb_robot_driver
[4] https://rosindustrial.org/
[5] https://github.com/qcr/armer

Figure 5: The ABB IRB6700-200/2.60 robot, located at the ARM Hub along with the experimental conveyor.

trollers have relied on the generation and execution of trajectories to move robot arms to desired poses, these controllers have largely relied on the assumption that the world is either static, or at least wholly predictable (e.g., car factories). The open-source ARMer package differs from these controllers by allowing the robot to utilise not only trajectories, but also a broad range of other real-time control primitives such as velocity control, positional servoing, and guarded motions, to provide a greater degree of control over the motions of the robot – particularly relevant to dynamic steel bars.

ARMer also facilitates the use of *agents*, which are responsible for deciding at any given moment which action should be applied, with respect to the overall mission objectives and its sensory inputs. This *agent* uses the behaviour trees framework, which has been implemented in our architecture using the *ros_trees*[6], *py_trees*[7], and *py_trees_ros*[8] Python libraries.

Behaviour trees were first introduced by the gaming industry as an alternative to Finite-State Machines (FSM) to define the behaviour of Non-Player Characters (NPC) in first-person shooters [Isla, 2005]. Since their inception, they have found increasing popularity within the gaming industry and are now showing value for robotics. Behaviour trees are a reactive AI formalism, and provide a number of advantages over FSMs, such as readability and scalability, while also providing an equal or greater degree of expressiveness when compared to FSMs and other control architectures such as Subsumption architectures [Colledanchise and Ögren, 2018].

5.2 On-Board Vision System

A distinct grasping method under visual control is considered an essential solution for conveyor-line problems [Luo and Liao, 2017]. Therefore, an Intel RealSense D455 sensor was utilised for this study, particularly as they: (a) have ready-to-go ROS packages for data extraction at high rates (noted maximums of approx. 30 Hz); (b) have a large baseline with global shutter; and (c) provide colour and depth information through their stereo-vision design. A Raspberry Pi 4b was mounted around the ABB end-effector; setup with Ubuntu 20.04 to run ROS on-board that launched the required nodes for the vision-based sensor on boot. A Power Over Ethernet (POE) shield enabled power input via Ethernet that was effortlessly routed through the standard ABB cable management. The mounting design took advantage of the RealSense's depth data with a downward facing implementation such that the camera stays clear of the gripper as well as the conveyor. Figure 6 shows the final design revision tested for this study.

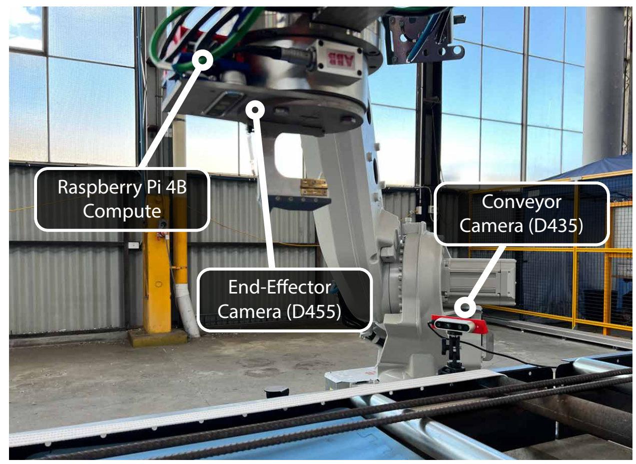

Figure 6: The camera mount design for the D455 sensor and Raspberry Pi 4b. A conveyor camera D435 was used for human tester visual confirmation and safety only.

The end-effector camera system performed two main actions: (a) initial detection of the bars when they arrive into view; and (b) reliable tracking of the target bar for extraction (Figure 9). Both these applications were designed as ROS nodes controlled by the overall behaviour tree agent. Detection involved processing the depth data from the RealSense D455 and clustering a lateral slice (conveyor width) using *k-means* clustering – a method that clusters points closest to K centroids. K, in this case, is the assumed number of bars. Each point from the point cloud essentially belongs to one of the bars travelling on the conveyor; presenting a quick method of bar classification.

As a stereo-vision system involves a relationship between depth and the baseline (distance) between the two sensor pair(s) [Keselman *et al.*, 2017], depth data would become unreliable during the extraction process. Therefore, a vision-based algorithm was also developed to continuously estimate the target bar's approximate

[6]https://github.com/qcr/ros_trees

[7]https://github.com/splintered-reality/py_trees

[8]https://github.com/splintered-reality/py_trees_ros

Three-Dimensional (3D) pose. This detection pipeline included: (a) masking a defined Region of Interest (ROI) from the captured image – using a blue background for simplicity; (b) performing an *adaptive threshold*[9] on the ROI – an algorithm that determines different threshold value(s) for each pixel based on a small neighboring region for better performance under varying illumination; and (c) performing *morphological operations*[10] on the processed ROI for robust contour identification.

The detected bar was tracked via Kalman filtering; an optimal state estimator for discrete-time linear time-invariant systems via the application of corrections [Corke, 2017]. Our detection/tracking pipeline successfully enabled visual servoing via the robot control framework to extract each of the bar types under static and moving cases (tested at an approx. max speed of $30\,\mathrm{cm\,s^{-1}}$). Not only does the detection/tracking work for each individual bar, it also handles extreme cases where: (a) the bars are laterally bunched due to motion; and (b) under changing lighting conditions (Figure 7).

Figure 7: The robust detection of the target bar amongst tightly arranged bars under varying lighting conditions. Note the green and red boxes highlight the target bar detected within multiple bars, respectively.

6 Full System Functionality

In this section, we present the overall functionality of the robotic passive extraction methodology. Note that the testing was conducted on a representative test setup at the Advanced Robotics for Manufacturing (ARM) Hub[11]. The intention of this feasibility study within the test setup is illustrated and compared with the real *in-situ* site in Figure 8; the objective being to extract the bars into a similar 'bay'.

[9]OpenCV Adaptive Threshold

[10]OpenCV Morphological Operations

[11]https://armhub.com.au/

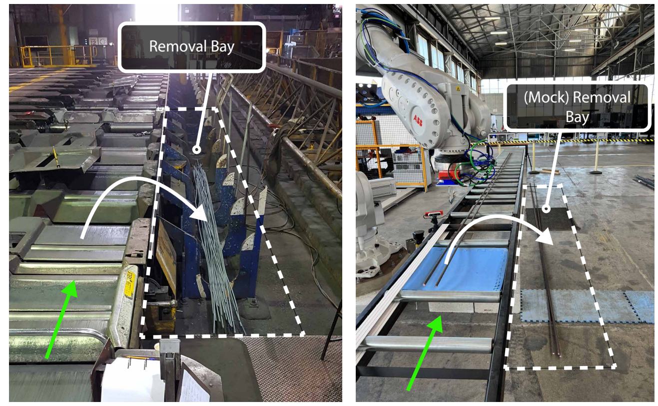

Figure 8: The target steel mill site (left) showing: (a) the travel direction of the bars (green arrow) on the conveyor; and (b) the removal bay. In comparison (right) is the test setup to replicate this.

A behaviour tree is the core of our robot control architecture. The explicit functionality of the tree is expressed as three *phases* of behaviours implemented for successful bar engagement and removal: (i) *phase one* – the end-effector visually servos to target bar; (ii) *phase two* – the soft engagement of the target bar; and (iii) *phase three* – full engagement and removal of the bar from the conveyor[12]. Note that a **high-priority check for user termination or workspace violation** – taking precedence over other behaviours – is computed every 30 Hz.

Phase one is a visual servo to close the gap between the next desired pose of the end-effector and the target bar. The overall process is summarised in Figure 9, where: (a) the target bar pose is identified by the detection/tracking pipeline; and (b) a minimal deviation path is computed towards said target pose. Note that this path is closed by reducing the error in the x axis (conveyor width) and z axis (vertical height) directions between the current pose and the target pose with respect to the robot base frame. A higher weight is given to the x axis error reduction to bring the tine vertically over the target bar as fast as possible. The servo speed functionality is controlled via the *ARMer* driver, beginning quick (approx. $15\,\mathrm{cm\,s^{-1}}$) and reducing in speed to approx. $3\,\mathrm{cm\,s^{-1}}$ for *phase two*.

Phase two is a 'soft' engagement to allow for bar motion on the conveyor while 'grasped'. The overall sequence of behaviours (Figure 2) takes into consideration the challenging 'bunched bar' scenario, where the passive gripper *pierces* between the bars to successfully capture the target bar. The proceeding actions (*rotation* and *soft engage*) are to separate the other side of the target bar, via the custom 'tooth' on the tine. The rotation element

[12]https://youtu.be/u0EqSnYjYsk

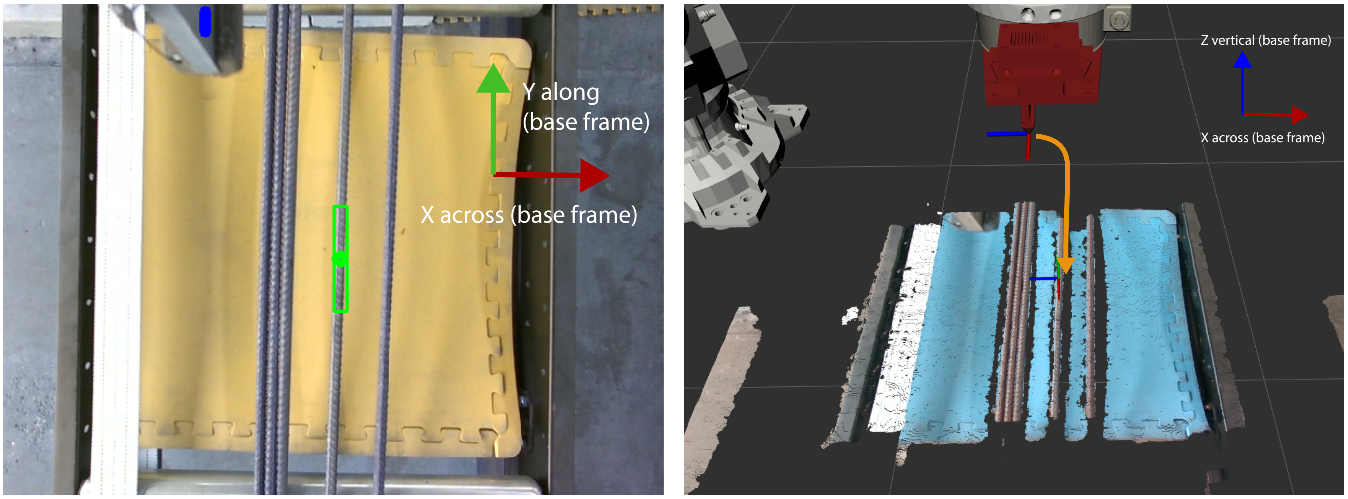

Figure 9: The servo to target bar process at a high-level. Note that: (left) represents the detected bar from the end-effector vision system; and (right) a ROS visualisation tool illustrating the intended motion.

easily makes the method applicable to changes in the bar diameter, where the diameter/width of the bar dictates how much the tine is required to rotate.

Phase three involves the full engagement and removal of the target bar. These sequence of actions: (a) conducts a fast upwards motion to *fully engage* the bar; and (b) completes a parabolic trajectory to remove the bar from the conveyor line. The parabolic motion to remove the bar is a predefined trajectory to ensure the safe and *expected* motion of the end-effector. These trajectories are pre-computed for a number of 'bins' at every 1 cm along the conveyor width (x axis direction from the robot base frame). An illustration of all the generated trajectories is provided in Figure 10, where it is important to note that: (a) the end position along the conveyor width (x axis) is constant for all trajectories to ensure the end-effector drops the target bar without conveyor collision; and (b) the height of each parabola is constrained to 20 cm, but can be changed depending on the intended functionality. The chosen trajectory is the closest to the current x axis position of the end-effector (after *phase one* and *phase two*). This allows for dynamic configuration depending on how much the bars move laterally during their forward motion. An approximate 180° rotation about the z axis (vertical with respect to the robot base frame) is accomplished to revolve the 'tooth' to *disengage* from the captured bar without additional joint motions. Disengaging the bar in this way allows the bar weight to naturally fall downwards, leading the remaining length of the bar (still on the conveyor) to 'whip' off due to the rotational moment (about the y axis – along the conveyor direction) under gravity. This pick up of the end and drop/whip-like action mimics the action taken by the human operators.

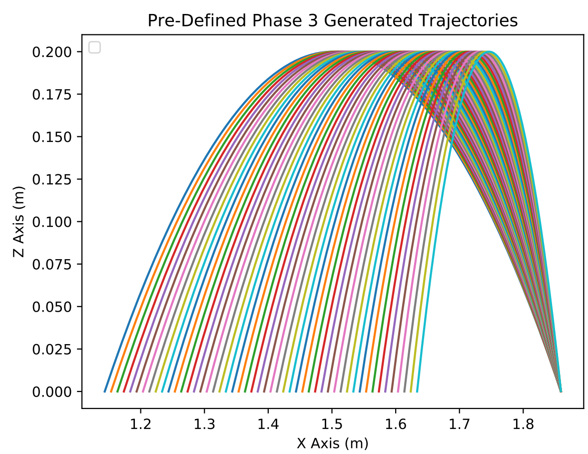

Figure 10: Multiple pre-defined trajectories generated for the *phase three* action. Note the 'bins' of multiple trajectories, that are selected based on the detected bar's lateral position on the conveyor, ending at a common point to consistently place bars in the removal bay.

7 Experimental Results

We performed pickup attempts until each bar location in a batch was successfully removed on three (3) occasions. Please note, for safety reasons, the 20 mm bar had a reduced batch size and limited number of attempts. The aim of the experiment was threefold: (a) to gauge obvious failure modes for future work consideration; (b) to confirm if bars placed laterally on the conveyor can be successfully removed while in motion; and (c) to assess whether an *industrial cobot* (with a lower payload capacity) could complete this task. The results are sum-

Table 1: Overall data summary for each type of bar. Average forces were calculated from successful attempts only. *Note the 20 mm bar forces are not statistically significant due to the experiment methodology.

Bar Type	Batch Size	Total Attempts	Vision Issues	Human Error	Pickup Issues	Ave. Max Force	Ave. Max Torque
10 mm	5	20	1	3	1	46.92 N	5.061 N m
12 mm	5	21	3	2	1	54.75 N	5.879 N m
20 mm*	2	2	N/A	N/A	N/A	145.42 N	10.06 N m

marised in Table 1.

A total of 20 and 21 attempts were recorded to meet the experimental criteria for the 10 mm and 12 mm bars respectively. 11 *unsuccessful* attempts were documented (combining both bar types captures), it is important to note that: (a) 4 cases did *not attempt* a pickup due to visual tracking unreliability: due to varied lighting conditions prevalent at the testing site; (b) 3 were *purposely cancelled* due to human error and not attributed to the system performance; (c) 2 cases successfully performed all three (3) *phases*, but were unsuccessful in removing the bar due to late operator input (considered human error); and (d) 2 cases had unsuccessful engagement encounters where: (i) one case (12 mm) successfully performed *phase one* but failed to engage the target bar (*phase two*) due to lateral motion on the conveyor; and (ii) the other case, a (10 mm) bar, performed the engagement (*phases one and two*) successfully, but failed to remove the bar from the conveyor through *phase three*. The average values of the force-torque experienced are documented in Table 1 for the successful attempts.

We examined the execution time for each *phase*. The *phase one* and *phase two* actions (grouped as one cohesive suite of actions) took on average approx. 9.94 s to complete. The pickup window (*phase three*) took on average approx. 3.22 s to execute. Although both these execution times could be faster, it was purposely reduced for safety considerations. The Cartesian velocity range achieved by the gripper during the removal phase was noted as between approx. $20\,\mathrm{cm\,s^{-1}}$ and $50\,\mathrm{cm\,s^{-1}}$.

8 Discussion and Future Work

Overall, the engagement and removal via the custom gripper was successful in this feasibility study, with most of the noted errors attributed to human error, as well as unreliable bar detection/tracking due to: (a) large lateral movements on the conveyor with respect to the end-effector downward motion; and/or (b) non-optimal lighting conditions experienced. The limitation in tracking the bars could be overcome by utilising a different, more suitable, sensing modality (i.e., a laser line depth extraction technique) over the RealSense depth camera utilised for this initial study. Furthermore, the lighting conditions *in situ* can be controlled in such a way as to limit variability in performance. These results (for the 12 mm and 10 mm bar types) indicate that an industrial *cobot* (such as a Universal Robotics (UR) model 10 – with a payload capacity of 10 kg) may be a viable option. Notably, although the mass of each bar can be quite large depending on their length, the force experienced during the engage and lift is a fraction of this.

The key contribution of this paper is the design and implementation of a passive grasping, closed-loop robotic steel bar removal system. This was conducted by an iterative design methodology with frequent testing and revision on a real robotic platform. The final outcomes and performance evaluation demonstrates: (a) vision-based sensing mechanisms can be effectively utilised towards the detection and tracking of the target bar towards a closed-loop feedback system for the robotic extraction; (b) the payload limitations, specifically those of the 12 mm and 10 mm bar variants, were deemed relatively negligible in the context of utilising a lower payload collaborative robot (cobot); and (c) the design of a custom end-effector gripper, purpose built for extraction of the target 'short' bar in a *passive* way that incorporated: (i) interchangeability in efficient replacement of the parts; (ii) repeatability of operation with a passive return of the gripper to its pre-grip state; and (iii) utility to all bar types in scope.

Future work will include: (a) additional vision-based sensing improvements to further alleviate issues under varying lighting conditions experienced; (b) further refinements to the gripper design, including a more robust return mechanism and the exploration of material science within the designed part; and (c) upgrades to the test setup to enable testing of: (i) moving 20 mm batched bars that was otherwise restricted due to safety; (ii) improved speed capability of the conveyor to achieve more representative results of a manufacturing site; and (iii) longer bars. Furthermore, the exploration of utilising a smaller payload capable robot (cobot) would result in added safety, and an overall reduction in cost.

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