The ANBOT: An Intelligent Robotic Co-worker for Industrial Abrasive Blasting

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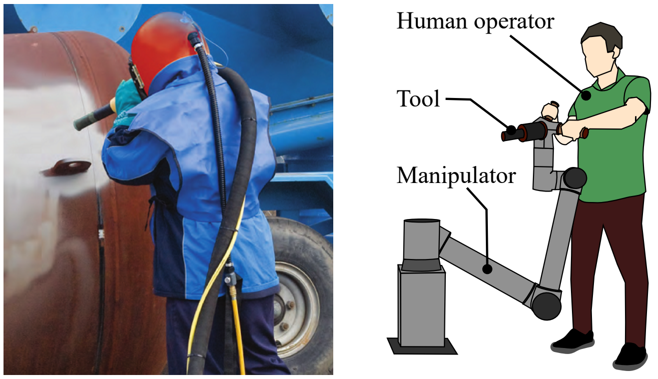
***Abstract*— We present the ANBOT, an intelligent robotic co-worker for physical human-robot collaboration. The ANBOT system assists workers performing industrial abrasive blasting, shielding them from the large forces experienced during this physically demanding task. The co-operative robotic system combines the strength and endurance of robots with the decision making of skilled workers. The inherent challenges in human-robot collaboration, combined with the difficult blasting environment required novel design decisions to be made and new solutions to be developed. These include an approach for handling kinematic singularities in a manner suitable for human-robot co-operation, estimating worker pose under poor visibility conditions, and an intuitive control scheme that adapts the robotic assistance based on the estimated strength of the worker. In this work we summarise the ANBOT system and present findings from preliminary site trials. The trials included several real industrial blasting tasks under the control of a skilled abrasive blasting worker who had no experience working alongside a robot. Results demonstrate the suitability of the ANBOT for practical industrial applications.**

I. INTRODUCTION

Despite the desire to improve occupational health and safety standards around the world there are still numerous industrial activities and processes that have significant risk of physical injury. Abrasive blasting, shown in Fig. 1a, is a particularly laborious task used in a wide range of industries, including steel bridge maintenance, manufacturing, construction, and the shipyard industry. Pressurized air or water is used to propel abrasive media onto a surface to smooth, roughen, reshape or remove contaminants such as rust, paint or graffiti. The heavy weight and large reaction force of the blasting nozzle puts significant physical burden on workers, with loads over 100N being typical [1]. Furthermore, workers often do not practice effective ergonomic principals as they perform their blasting duties [2]. Vibrations are also a hazard, with cases of blasting workers reporting hand-arm vibration syndrome (HAVS) caused by exposure to vibrations over a long period of time [3]. Abrasive blasting is a dirty, dangerous and labour intensive task that today is predominantly conducted by humans.



(a) Manual abrasive blasting (b) Co-operative robotic system

Fig. 1. (a) A typical abrasive blasting scenario. The nozzle weight and blasting reaction loads put significant physical burden on workers. (b) Example showing a collaborative robot to assist a human operator during an industrial task. Controlled by the worker via direct physical interaction, the robot assists the worker by supporting the task loads.

For abrasive blasting and other physically demanding applications, collaborative robots working in co-operation with human workers have the potential to reduce the physical burden of tasks, leading to reduced risk of physical injury, improved working conditions and higher productivity. Fig. 1b depicts a collaborative robotic manipulator working with a human performing a task using a tool attached to the end-effector. Motions of the tool are controlled by the human worker exchanging forces with the robot, which assists the worker by guiding the tool and supporting the physical workload. This co-operation utilizes the complimentary strengths of both parties, the strength, precision and endurance of the robot, paired with the skill, intuition and decision making abilities of the worker.

The harsh blasting environment presents several challenges for robots. Airborne particulate from the blasting process significantly reduces visibility. The system is subjected to ricocheting abrasive, requiring protection of all system components. Any robotic system designed to operate in these conditions needs to overcome all these challenges. Previously, the robot *Alpha 1* [4][5] has been developed for autonomous abrasive blasting. It operates by using sensors to first build a 3D representation of the environment, then plan the blasting trajectory and execute it. Environment scanning is done before blasting to minimise the impact on visibility. This system improves safety by removing workers from the environment during the blasting portion of the process. In contrast, a co-operative robotic system for blasting requires a human to work proximal to the robot, controlling its motions to dictate the blasting process. This co-operative paradigm creates additional challenges. An intelligent robotic co-worker requires information about the human and their environment. The poor visibility during blasting makes ob-

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taining this information difficult. Identifying and tracking the worker is made more difficult by workers wearing personal protective equipment. Consideration is also needed as to how the robot administers assistance to the worker, with collisions and kinematic singularities handled in an appropriate manner. Despite the additional challenges, a co-operative blasting robot may be preferred as it allows the expertise and decision making skills of the worker to be utilised.

This paper presents the design, development and testing of a world-first intelligent robotic co-worker for assisting human workers performing abrasive blasting. Named the ANBOT (*A*ssistance as *N*eeded ro*BOT*), the system combines a collaborative manipulator with specially developed mounting solution, end-effector, sensing capabilities and control algorithms to reduce the physical burden of abrasive blasting. Solutions developed have wide applicability, for blasting applications and for practical co-operative robotic systems in general. In Section II we present the overall system and detail the design decisions made during development. Section III details the control architecture developed to achieve safe and intelligent co-operation with workers. Unique to this implementation is an adaptive assistance paradigm. In Section IV we detail outcomes from field trials in which the system successfully assisted workers skilled in blasting but have never before used a robotic system.

II. SYSTEM OVERVIEW

The ANBOT, shown in Fig. 2, is a portable robotic system consisting of a collaborative robotic manipulator, a custom end-effector, transportable mounting solution, integrated control module and a camera-array housing. With the blasting nozzle attached to the end-effector, a worker can perform blasting operations by controlling the system via direct force interaction with a pair of handles.

A. *Collaborative Manipulator*

At the core of the system is a UR10 collaborative manipulator from Universal Robots. The UR10 was chosen as it was one of the first collaborative robots commercially available and certified for safe physical human-robot interaction. Additionally, the 10kg payload capacity was large enough to support the type of blasting operations being considered.

Another factor in choosing the UR10 was the 1.3m reach, which is larger than most comparable collaborative robots. The larger reach provides the human worker with a larger workspace to work in. This is important as the ANBOT base is not intended to move during operation, hence a small manipulator workspace would restrict the worker. Furthermore, a larger workspace reduced the likelihood of performing operations that put the robot near singular configurations. This can be detrimental to robot performance, and is discussed further in Section III-B.

The decision to use a serial manipulator was based on the application requirements. In abrasive blasting the direction of the reaction force depends on nozzle orientation. A manipulator is capable of supporting loads in all directions. This is in contrast to overhead cable-based support systems such as Intelligent Assist Devices (IADs) [6] used for materials handling where the load to be supported is in the direction of gravity. The design of an upper limb exoskeleton was explored but eventually dismissed given the large payload requirements and the concern that a wearable robot may interfere with the worker's personal protective equipment. Furthermore, to transmit blasting loads to the ground would require either a full-body exoskeleton or a floor-mounted upper limb exoskeleton. The manipulator was chosen as it was considered a more suitable alternative which can be utilised much like a Human Extender [7] to support both gravity and reaction loads in all directions by transmitting them to the ground on which it stands.

Fig. 2. The ANBOT, a collaborative robotic system for assisting workers during industrial abrasive blasting.

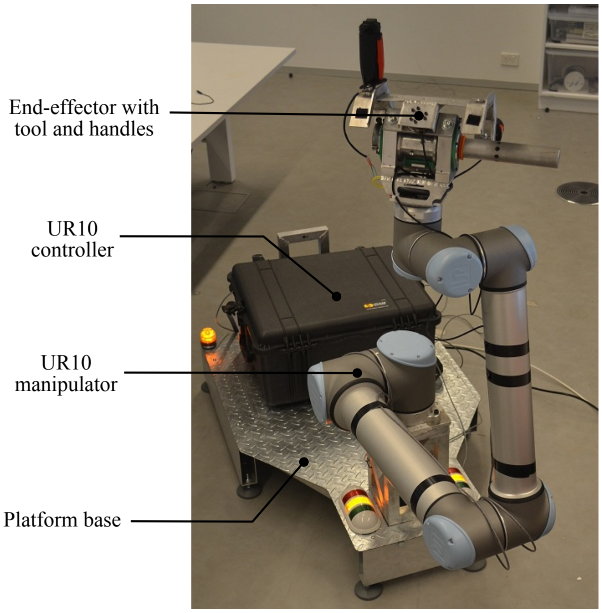

Fig. 3. A version of the ANBOT system during development. The protective covers are removed so that the system components can be seen.

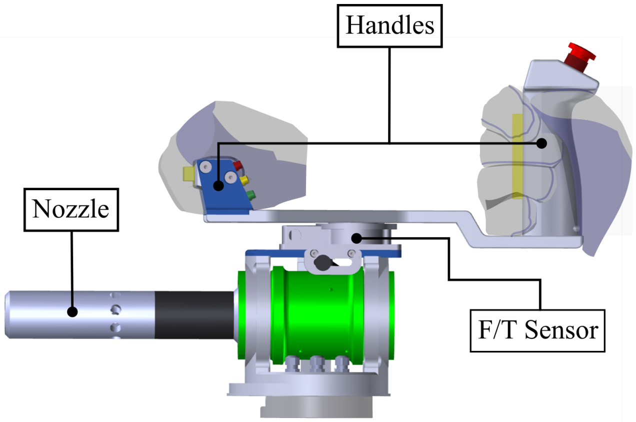

Fig. 4. The custom end-effector allows the blasting nozzle to be mounted to the robot and facilitates user control of the system. An integrated force-torque sensor measures the interaction between the robot and worker.

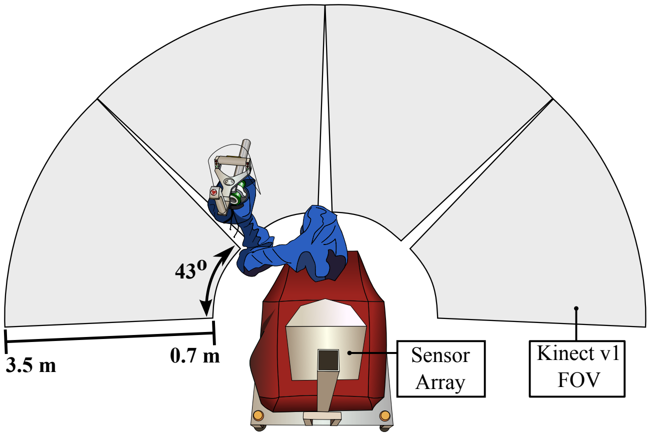

Fig. 5. The field of view of the Kinect V1 camera array mounted to the ANBOT base.

B. End-effector

To facilitate robot-assisted blasting a custom end-effector was developed. Design of the end-effector was guided by user feedback, with several iterations tested. The final design shown in Fig. 4 allows for ambidextrous operation. Two handles provide well-defined interaction points for the human to control the system. Safety rated switches integrated into the handles activate the motion of the robot and enable the flow of abrasive media through the nozzle. Brightly coloured indicators mounted next to the front handle in line of sight of the worker allow the operating state of the system to be visualized even in poor visibility.

The control of the system, detailed in Section III, requires measurement of the worker interaction with the handles. An integrated 6-axis force-torque sensor (ATI Mini-45) positioned between the handles and the blasting nozzle allows a worker to maneuver the end-effector directly through physical interaction. A custom designed housing protects the sensor from the harsh operating environment whilst still allowing force and torque measurements to be made.

C. Portable Base and Controller Enclosure

Abrasive blasting is often performed on site. Therefore the ANBOT was developed as a transportable, completely self-contained system that can be deployed wherever abrasive blasting is required. The small footprint, roughly 0.8m by 1.2m, allows for transportation through doorways and elevators by means of a pallet jack. The footprint also allows the worker to be standing on the floor next to the manipulator, rather than on the base itself, reducing the risk of tripping over or falling off the edge of the base whilst blasting. Stability was improved by using the controller and associated electronics as ballast. The IP67 rated controller enclosure contained all the electronics for operating the system. Inside was the standard UR10 robot controller, signal conditioning electronics for the force-torque sensor, and computer (Intel i7 7700K processor, 16GB of RAM) for implementing the control loop, trajectory calculations and vision processing. If needed, the enclosure can be removed from the base for easy transportation.

D. Environmental Protection

During operation the system will be subjected to airborne particulates and ricocheting abrasive material. Several layers of protection were utilised to shield the system from the challenging environment. The controller and electronics were all contained within an IP67 enclosure. An inner cover surrounding the manipulator from base to end-effector provided a physical barrier against ingress. A thicker outer cover surrounded the manipulator and base which protected it from the ricochet of abrasive material blasted from the nozzle. A vortex cooler was used with compressed air fed into the controller enclosure to keep internal temperatures to appropriate levels whilst simultaneously pressurising the enclosure for added ingress protection.

E. Environmental Sensing

An array of 3D sensing cameras was mounted behind the robot to measure the human worker and their surroundings. This sensing facilitates intelligent system behaviour such as avoiding collision with the environment, or tracking the pose and movements of the worker pose and adapting the physical assistance strategy accordingly. The system has four Microsoft Kinect V1 sensors arranged in an array such that they provide a combined 180° RGB-D view of the workspace as seen in Fig. 5.

The type of abrasive medium used greatly impacted the sensing data quality, with garnet creating significantly more interference compared to using steel grit. Both Kinect V1 and V2 cameras were tested and compared. The Kinect V1 was chosen as it was able to better detect the human worker during blasting. The difference between the depth image data provided by the two cameras can be seen in Fig. 6.

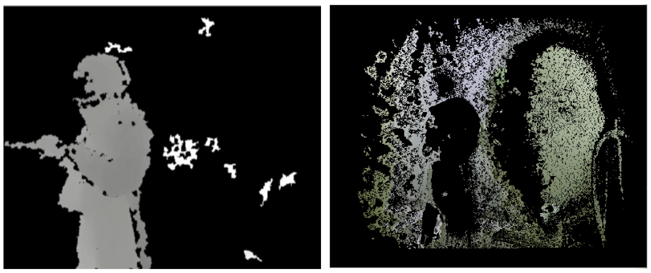

Fig. 6. Difference in performance between the Kinect V1 camera using structured light (left) and the Kinect V2 camera using time of flight (right).

F. Operator Safety

A critical requirement of any collaborative robot system is maintaining the safety of the human operator. This facet was considered in all design aspects of the ANBOT. The UR10 is a collaborative robot designed to meet standards regarding physical human-robot interaction. Commands that are sent to the UR10 controller for execution are subject to maximum force, speed, energy and other limitations set by these standards. Movement of the UR10 is enabled only when the 3-position switches on the handles are pressed. Only when both switches are enabled is abrasive material expelled from the nozzle, achieved by electrically connecting the blasting equipment to the UR10 controller. This arrangement means that robot error states automatically inhibit blasting from being performed. The third position of each switch is used to halt the robot and blasting in the case of increased hand grasp. Previous work found that during human-robot collaboration, unexpected robot behaviours cause the human to increase their grasp [8].

Safety was a key consideration when developing the control architecture that governs the robotic assistance given to the worker. It is important that interaction with the system be intuitive and easy to use. It is hypothesised that removing the physical burden from the task might lead to a "false sense of security" with workers discounting the inherent danger in the task. This paradoxical concern means that providing assistance to the worker may actually increase risk. Also, a static level of assistance can lead to lower levels of user engagement and concentration [9]. For this reason a novel adaptive assistance scheme has been implemented. Details on the ANBOT control architecture are provided in the following section.

III. CONTROL ARCHITECTURE

Unlike the autonomous blasting robot implemented in [5], the ANBOT is in direct physical contact with a human operator. Generally, both the physical and psychological reactions of the operator have to be taken into account when implementing a control system for physical human-robot interaction. As collaborative robots are relative newcomers to the industrial market, new human-robot control paradigms are a topic of interest for researchers.

A. Admittance Control

Smooth interaction between the worker and the ANBOT was achieved using an admittance control scheme based on [10]. Fig. 7 shows the control system. Interaction forces and torques between the operator and the handles are measured by the integrated force-torque sensor. These forces $\mathbf{F}_I$ represent the worker's intention. They are multiplied by admittance matrix $\mathbf{K}_A$ to generate Cartesian velocity command $\dot{\mathbf{x}}_d = \mathbf{K}_A \cdot \mathbf{F}_I$. The Cartesian velocities are transformed to joint velocities $\dot{\mathbf{q}}_d$ using the inverse Jacobian matrix, which are then sent to the Universal Robot controller as joint velocity commands. The admittance control scheme also allows factors such as singularities, collisions and adaptive assistance to be integrated.

B. Singularity Handling

Kinematic singularity occurs in configurations where the Jacobian matrix loses rank. More intuitively, this corresponds to the robot losing the ability to move the end-effector in particular directions. It is well understood that robot performance deteriorates near kinematic singularity. Despite numerous solutions for handling singularities available in the literature, few have been developed with physical human-robot interaction in mind.

A framework for handling singularities was developed specifically with human interaction in mind [11]. The modified inverted Jacobian matrix $\mathbf{J}^*$ is formulated in a way that applies damping to the motions of the robot near singularities in a manner well suited for physical human-robot interaction. Bounded virtual forces $\mathbf{F}_S$ discouraged the user from approaching singular configurations. Additionally, the framework used an asymmetric damping scheme which applied different damping behaviours depending if the robot is moving towards or away from singularity. Combined, these techniques were found to greatly improve the control experience for the worker when operating near singular configurations.

C. Collision Avoidance

Collisions need to be avoided to prevent damage to both the robot and surrounding objects. Robots that execute pre-planned trajectories can check for collisions during the path planning stage. In the ANBOT system, motions are calculated instantaneously depending on worker interaction, hence collision avoidance via path-planning is not suitable. Our solution continuously checks for potential collisions based on its current configuration. When a collision is identified, a local search is performed to determine the distance between the current configuration of the robot and the configuration in which collision occurs. A repulsive force $\mathbf{F}_C$ proportional to this distance is computed to smoothly guide the user away from the collision. For self collisions a geometric model of the manipulator is used. For collisions with the environment an occupancy grid representation shown in Fig. 8 and based on the environmental sensing mentioned in Section II-E is used.

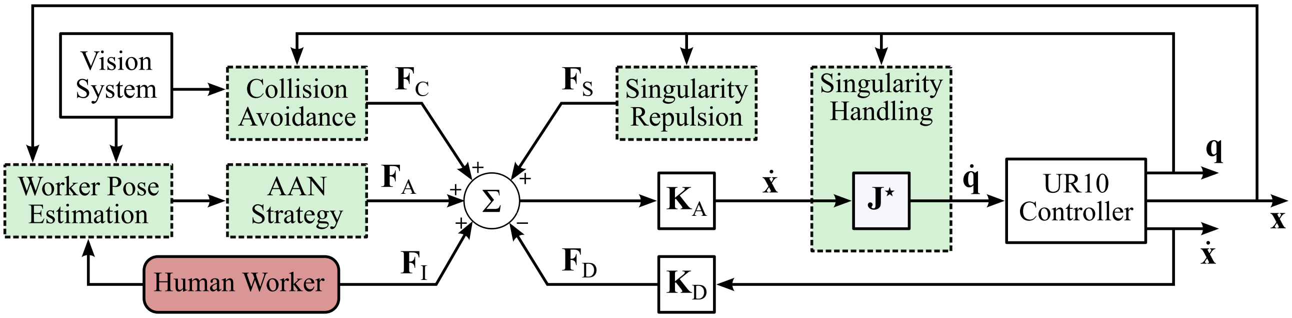

Fig. 7. The ANBOT control system.

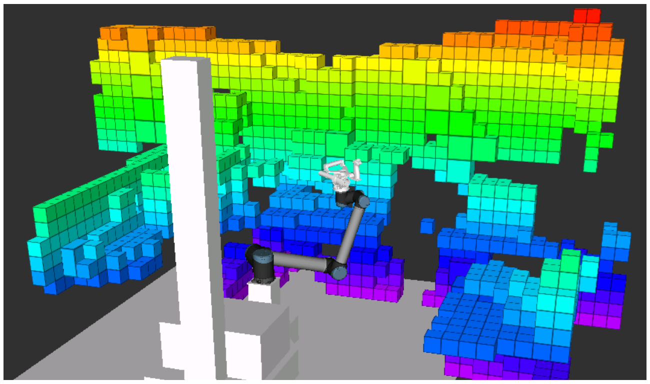

Fig. 8. Example of the occupancy grid representing the environment around the ANBOT. The representation is constructed using the on-board array of 3D cameras and is used for collision avoidance with the environment.

D. *Worker Pose Estimation*

By measuring the pose and motions of the worker the system can adapt its behaviour. This is an important ability if we want collaborative robotic systems to be intelligent co-workers. Knowing the worker pose is also a requirement for implementing the adaptive assistance scheme presented in the following subsection.

Measuring the worker pose is difficult as vision-based sensors are subject to interference in the blasting environment, and the close proximity of the worker to the robot can cause occlusions between the worker and cameras. A solution was developed for measuring the worker pose that exploits kinematic information about the worker [12]. The known locations of the worker's hands on the handles were used as kinematic constraints, along with an upper body biomechanical model to limit the pose estimation to humanly feasibly poses. This was a significant benefit over existing methods which computed largely erroneous and humanly impossible body poses when visibility was poor.

E. *Assistance-As-Needed strategy*

An Assistance-As-Needed (AAN) strategy was developed and implemented into the ANBOT for the purpose of maintaining worker engagement during tasks. Studies demonstrate that human performance is degraded during low-engagement activities [9]. AAN paradigms have been explored and shown to achieve benefits in robotic rehabilitation, however their use for industrial activities has to date received little attention.

The AAN strategy developed and implemented in the ANBOT provides an assistance inversely proportional to the estimated strength of the worker. A model of the upper limb [13] show in Fig. 9 was used to estimate worker strength and develop the paradigm [14]. We define the strength capacity as the maximum force that the human body can exert in a set of conditions (e.g. pose, reduced abilities, etc.). The force that the worker is required to support is proportional to the estimated strength capacity as calculated using the strength model.

Given the limited area in front of the torso that the operator uses while blasting, the estimated strength capacity of the worker as they perform a blasting task might not vary significantly. We normalise the calculated strength of the worker over a defined strength range. Defining F as the force that the operator has to contribute to the task, F_{max} as the maximum force that they can be supported with, S the estimated strength capacity (calculated from the upper limb model), S_{max} and S_{min} as the maximum and minimum strength capacity in the task workspace, it is possible to obtain:

$$F = F_{max} \cdot \frac{S - S_{min}}{S_{max} - S_{min}} \qquad (1)$$

Values for the minimum and maximum strength capacity (S_{min} and S_{max}) in (1) are chosen empirically, exploring the human body configurations that are more likely to be required during task execution. The robot is responsible of assisting the operator with the remaining external load.

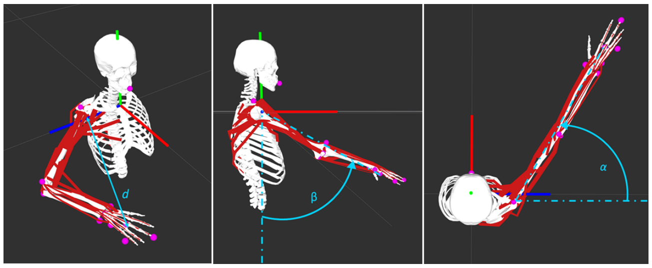

Fig. 9. Three dimensions used to discretize the human operational workspace.

The calculation of the strength capacity is a computationally demanding process, because of the complex musculoskeletal model and due to the optimization procedures involved. In order to achieve a real-time implementation of AAN, some simplifications were required. The aim was to have worker strength capacity values for all hand positions across the workspace, without the necessity of computing them online. To simplify further the process, the external force is considered a function of the hand position, and in a defined direction pointing from the hand to the torso. Another simplification was to implement only a single upper limb strength model (the right upper limb) and mirror the model to represent the left arm. Additionally, we make the assumption that the wrist strength of the worker is not a limiting factor in the task. We reduce the upper limb model from 7 degrees of freedom down to 4 by neglecting the human wrist. All of the above simplifications greatly decrease the number of variables involved in the computation of the strength capacity.

With the aforementioned simplifications made, it is possible to estimate the user's strength capacity relative to each pose of the upper limb. The upper limb pose and the corresponding strength capacity are computed offline for a set of points in the operative workspace. The obtained strength capacity is then fitted with a third-degree curve-fitting procedure, which uses least-squares. With this approach, the strength capacity can be estimated without addressing the several redundancies in the model for every position of the user's hands. The resultant offline estimation is less accurate than the one obtained with an online optimisation, but for the purpose of this work a high accuracy is not required. Also, the external load that the operator has to sustain is limited to 10 N, which is much lower the usual payload an operator has to sustain during traditional abrasive blasting.

The position of the hand is computed in the 3D space with respect to the torso, with the latter being tracked by the vision system. The computation of the upper limb pose results in a kinematically redundant problem. The redundancy of the human arm is resolved optimizing the elbow swivel angle [15] with a primal-dual interior-point optimization method [16].

The pose of the worker is a requirement for the AAN strategy. A policy is implemented for the case where the pose of the worker is unable to be measured. For the first two seconds after pose tracking has failed the AAN strategy will continue to use the last measured pose. If the pose is still unobtainable for the next 13 seconds, the assistance is changed such that the ANBOT supports the entire blasting load. If the worker pose is not able to be measured after more than 15 seconds, a protective stop is issued.

The main goal of this AAN strategy is to keep the user focused and aware of the blasting task. There are several advantages an adaptive assistance scheme may provide, such as increasing assistance as workers become fatigued, or when workers adopt non-ergonomic poses. Such adaptive assistance schemes are currently the focus of active research. There are many open questions and obvious challenges. The ANBOT is the first known example of an AAN strategy to be employed of a robot of this kind.

IV. FIELD TESTING

Field tests were performed on site in a blasting chamber of Burwell Technologies, Australia's leading manufacturer and distributor of equipment for the surface preparation industry. To our knowledge this is the first time a co-operative robotic system has been used by a worker to perform genuine blasting operations. Fig. 10 shows the ANBOT during site trials. Multiple tests were conducted with blasting performed by an experienced worker to evaluate the performance and capabilities of the system in authentic abrasive blasting scenarios. Aspects of the system evaluated included the ability of the system to withstand reaction forces from abrasive blasting, intuitiveness of the physical human-robot interaction, and general acceptance of the system by skilled workers.

A. Testing Without Abrasive Media at Reduced Pressure

The first test conducted was a dry run at 60 psi where the abrasive media was not supplied. The decision to not use abrasive in the initial tests were due to uncertainty as to how the UR10 would respond to the reaction load. Using air without abrasive meant the reaction forces would be less than if abrasive media were used.

(a)

(b)

Fig. 10. (a) The ANBOT tested in laboratory conditions in preparation for site trials. (b) The ANBOT being used by an experience worker to perform real abrasive blasting during a site trial.

During this testing the experienced blaster operated the robot to simulate a blasting task. Feedback from the worker was overall positive, however the limited workspace of the robot and poor performance near singularity was criticized. The singularity experienced by the worker was due to the manipulator elbow joint becoming straightened. A simplistic method for handling singularities was used. The poor feedback motivated the development of a new method, as described in Section III-B. Despite this, the UR10 functioned as intended, supporting the reaction loads without entering any emergency or protective stop modes. Based on these results the next trial using abrasive media was planned.

B. Testing With Abrasive Media at Full Pressure

For the second field test the system was used in the same blasting chamber with the same experienced worker. Unlike the previous test, real abrasive blasting was performed using steel grit. Blasting air pressure was started at 60 psi and incrementally increased to a normal operating pressure of 110 psi. Forces measured by the UR10 at the end-effector were just under 100N on average at this higher pressure. Like the previous test it was found that the UR10 could withstand the reaction loads without issues of safety or triggering safety stops from the UR10 controller. The specially developed cover protected robot and electronics sufficiently, with very little grit found under the cover.

The worker performing the testing had an improved impression of the system compared to the previous dry test. When performing an actual abrasive blasting task with abrasive media, the benefits of the system were more evident to the worker. By utilizing the ANBOT the reaction forces onto the worker were largely reduced. Peak forces applied to the worker in the direction of the nozzle were measured to be 20N, which reduced to approximately 13N during operation. These forces are significantly lower than in the case of traditional blasting.

Improved feedback regarding the workspace was also received. This is attributed to the method utilized for handling robot operation near singularities [11], which was not present in the test prior.

C. Testing with adaptive assistance

A trial was performed with the same worker using the AAN scheme implemented, compared to with a constant level of assistance applied. Feedback was that the worker did not perceive significant difference between the two methods. This is attributed to the fact that the worker is experienced with sustaining higher loads for extended periods. The range of assistance variation was set to a conservative value of 10N. It is likely this range was too small for the worker to perceive. The worker did provide positive feedback about a reduced feeling of fatigue compared to traditional blasting.

D. Impulse Reaction Loads

During the prior tests concerns were raised by experienced blasting workers about a common phenomenon during abrasive blasting. In some abrasive blasting setups the flow of grit can be inconsistent. A build up of grit in the pipeline can lead to surges of abrasive, resulting in larger impulse loads at the blasting nozzle. These impulses are generally random and causes the blasting nozzle to be difficult to control.

A test was conducted to simulate this undesirable condition. Grit was allowed to accumulate while the air supply was turned off, resulting in impulses when the air was turned on. The system functioned normally despite the impulse loads generated. Feedback from the worker in this test was also positive, noting that they did not feel that control of the blasting nozzle was an issue.

V. DISCUSSION

Motivated by increasing productivity and improving work safety standards, it is anticipated that co-operative robotic systems like the ANBOT will be of interest for a variety of industrial sectors. However, for systems like the ANBOT to be adopted it is important that the system not only work well, but also present a practical cost-benefit ratio. The largest expense of the ANBOT is the UR10 collaborative manipulator. The collaborative robot sector is growing, estimated to increase roughly tenfold between 2015 and 2020 [17]. The cost of collaborative robots are anticipated to reduce as their market-share increases.

A general concern is the notion of robots replacing human workers. Unlike fully autonomous robots, or traditional non-collaborative industrial robots, the ANBOT does not take the place of a human worker. The system complements human workers, combining the strength, endurance and precision of the robot with the skill and decision making abilities of expert workers. The purpose of the ANBOT is not to replace skilled labour, but instead be a tool that helps skilled labourers reduce risk of injury and fatigue.

A driver for adopting technology like the ANBOT is increasing occupational health and safety. The abrasive blasting industry has long been seeking to improve safety standards. Historical efforts have focused on respiratory dangers, primarily relating to airborne crystalline silica [18]. Given the danger of physical injury inherent in the task, using technology to reduce physical burden is an attractive direction for the industry. The payload capacity of the ANBOT (10kg) is enough to fully compensate the loads experience during common blasting applications, totally removing this physical burden from workers.

Workers who used the ANBOT in trials reported being less fatigued after a robot-aided operation, if compared to traditional methods. Whether the adaptive assistance strategy results in increased engagement is not yet clear. The workers's performances were affected by the novelty of the technology, and as a result they were fully engaged in the task. The way the nozzle was held was affected by previous blasting experience with traditional equipment. With the introduction of new technology workers may start moving the nozzle in a different way, which would affect the task workspace and consequently the assistance provided.

VI. CONCLUSION

In this paper we presented the ANBOT, a world-first co-operative robotic system for abrasive blasting. Detailed is the design, development and testing of the system to assist workers in practical blasting applications. The challenges inherent in human-robot collaboration, combined with the difficult blasting environment required novel design decisions to be made and new solutions to be developed. Field trials had workers skilled in abrasive blasting, but had never used a robot, utilise the ANBOT in real abrasive blasting tasks. The outcomes demonstrate the practicality of the ANBOT to assist worker during this physically demanding task. The design decisions and resulting outcomes have wide implications, both for blasting applications and for practical co-operative robotic systems in general.

APPENDIX

Video summary of the ANBOT project is available online: `https://youtu.be/p-eWnI1TJ64`

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