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The development and evaluation of Robot Light Skin: A novel robot signalling system to improve communication in industrial human–robot collaboration

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A R T I C L E I N F O

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A B S T R A C T

In a human–robot collaborative production system, the robot could make request for interaction or notify the human operator if an uncertainty arises. Conventional industrial tower lights were designed for generic machine signalling purposes which may not be the ultimate solution for robot signalling in a collaborative setting. In this type of system, human operators could be monitoring multiple robots while carrying out a manual task so it is important to minimise the diversion of their attention. This paper presents a novel robot signalling solution, the Robot Light Skin (RLS),which is an integrated signalling system that could be used on most articulated robots. Our experiment was conducted to validate this concept in terms of its effect on improving operator's reaction time, hit-rate, awareness and task performance. The results showed that participants reacted faster to the RLS as well as achieved higher hit-rate. An eye tracker was used in the experiment which shows a reduction in diversion away from the manual task when using the RLS. Future study should explore the effect of the RLS concept on large-scale systems and multi-robot systems.

1. Introduction

The use of industrial robots has been continuously increasing to meet rising global demands in manufacturing output and quality as well as reducing operating cost [1]. While most of these robots are designed to perform fully automated routine operations within caged areas, the recently introduced collaborative robots are designed to function alongside human operators and in some cases cooperate with them. Collaborative systems are offered as semi-automated solutions to manufacturing applications where there are variability in the components, procedures or operating environment that may require manual input from human operators [2,3]. These systems can provide the cognitive flexibility of human workers and the repeatability and robustness of industrial robots. In collaborative systems, humans and robots are sharing workspaces and often one human operator can be managing multiple robots while carrying out other tasks. In this case, robots must communicate with the operator effectively to maintain safe and seamless interactions.

In conventional industrial settings, tower lights are commonly used for visual signalling of factory production cells. Small assembly lines or cells are often operating in parallel with one tower light placed above the last station along the transportation aisle indicating the state of operation. In the context of visual management, tower lights are known as Andon lights, which support lean production systems as a means of indicating machines' status; one of the early adopter was the Toyota Production System [4,5]. Andon light is one aspect of the Jidoka manufacturing principle which refers to the practice of stopping work immediately when a problem occurs. It can provide visual signals to indicate the present of wastes in a factory, which are often the main source of potential improvements in business performance. An effective visual signalling system ensures that line status could be observed at a glance which then enable operators to alert relevant personnel for assistance [6–8].

Industrial tower lights are based on a simple system that is used in everyday life: the traffic light system. The main benefit of tower lights with red, yellow and green lights is a simple and effective communication tool which allows factory managers and supervisors to be aware of the state of production lines at a glance [9]. The intention is to enable users to perceive machines' state without the requirement for significant cognitive workload which will speed up the users' response time to the signals as well as reserving mental capacity to focus on other tasks. Apart from traffic signals and factory systems, the traffic light concept is also used in other ordinary applications. For example, in supermarket self-checkout each counter is equipped with one tower

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light which is usually positioned above the machine to indicate whether it is in normal working order or when attention is needed. In the event if an error occurs, the tower light changes from green to red to indicate human help is needed, and a contact staff will approach the machine when they notice the signal. In this case, the response time of the contact staff is largely dependent on the ease of noticing this visual signal [10–12]. Despite the evidential advantages shown in conventional factory systems, tower lights were not design specifically for human–robot collaborative applications so their efficacy can be significantly reduced. For instance, the positioning of tower light is restricted in a way that should not hinder the movement of the robot. On the other hand, the distanced light signals can divert operators' attention away from the robot and the manual task. Thus, the main aim of our study is to explore the key impacts of an alternative indication system on human–robot collaboration.

Human-machine interface developments are often technology-focused, where display of data in these systems is designed solely based on technical specification; it is often arranged in a way that is not ideally suited to support human tasks. Using such approaches could result with negative effects on the user performance, which can cause design-induced errors [13]. By applying the philosophy of user-centred design throughout the system design cycle, an effective collaborative system is achievable. A user-centred design challenges designers to build human-machine interfaces around the capabilities of the potential users. It also improves user acceptance and satisfaction as a side benefit [14]. When designing a communication system for human–robot collaborative working, it is important to consider human perception of signals in order to develop an effective system. For instance, in an industrial human–robot collaboration scenario, an operator could be carrying out a manual task whilst monitoring one or more robots. In a collaborative working environment, a robot could make requests for interaction to complete a task jointly with an operator, or when an abnormality is detected an intervention would be required. The robot will signal to the operator and must catch the operator's attention, who might be focused on a different task at that point.

Humans in general have limited capacity in paying attention to multiple events due to their information processing bottlenecks, people withdraw from some tasks in order to collaborate effectively with others [15]. Industrial tower lights are typically fixed at a location near the machine, and operators have to draw their visual attention to the light unit to detect any changes of light. This is an example of top-down spatial attention where the subject can focus on a small region of space within their field of view based on internal guidance of attention based on prior knowledge and current goals [16]. Thus, extra mental capacity is needed to extract useful information which could lead to higher than necessary workload and error. Humans react involuntarily to salient events as well as pay attention to objects which are relevant to their current activity. Visual attention is highly affected by the salience of objects (i.e. their size, colour, location) which can be defined as bottom-up attention [17,18]. Furthermore, research evidences have shown that bottom-up attention is faster than top-down attention due to it being an automatic reaction triggered by sensory information through the brain [19–25]. In this case, it is logical to minimise the number of objects which require visual attention within a collaborative robotic cell. Thus, the signalling interface should be an integrated system on the robot to provide dynamic visual signals which can be captured by users with ease using bottom-up attention.

Reaction time (RT) is another important aspect to take into consideration in this research because every second of system downtime could be costly for any production line. Therefore, a human–robot interface must be able to deliver signals to users as quickly as possible. Murray and Caldwell reported significantly longer RTs as the number of displays and display figures to be monitored increased, which supports the Hick's Law where decision time increases with the number of choices [26,27]. Humans' reaction to signals can also be delayed as an effect of increases in RT as viewing angle increased [28], as well as background noise [29] and task complexity [30]. Based on the limitation of viewing angle and position of traditional stack lights, users may have to rely on their peripheral vision to receive the light signal. However, several studies have shown that it usually takes longer for people to notice abnormalities in their peripheral vision [31,32]. This further supports the theory that visual signal should be within proximity of the area of interest for the particular application.

Majority of studies carried out on human–robot interaction through visual signalling are in the context of social and mobile robots, but little work has focused on industrial human–robot collaborative system [33]. Thus, the aim of this research is to develop and evaluate a visual signalling system concept specifically designed for collaborative production system which enables the operator to react promptly to a robot signal during a manufacturing operation.

The rest of the paper is organised as follows: Section 2 describes the proposed signalling system concept. Section 3 describes the methodology for validation of the concept and Section 4 discusses the experiment results. Finally, Section 5 concludes the paper with suggestions made for future work.

2. Robot Light Skin

2.1. The proposed solution

This paper proposes the Robot Light Skin (RLS) concept as a visual indication system which communicates robots' status to human operators. The device will cover the upper arm and wrist area of articulated robots, and it illuminates in different colours to indicate the state of the robot as illustrated in Fig. 1. In this case, the robot becomes the source of the signal and unlike conventional indication systems; it does not create another distraction for human workers. This enables operators to response to interaction requests from corresponding robots promptly and accurately as illustrated in Fig. 2. This concept could be realised using organic light-emitting diode (OLED) or light-emitting diode (LED) array, both are flexible and fully programmable which could be used to cover the exterior of an industrial robot as a signal light or for displaying text form status. However, the cost of OLED light sheet is relatively high compared to other viable lighting technologies such as fully programmable LED light strips. The cost of this technology should eventually decrease from the current level which enables it to be a feasibly low cost solution. Furthermore, the developed concept will be relatively simple to implement onto collaborative systems or retrofitted to existing production systems when compared with other interactive technologies such as Virtual Reality (VR) [42,43] and Augmented Reality (AR) [39,40]. It can also be integrated with other interactive devices such as tactile sensing modules [41] or combined with other safety strategy such as collision avoidance [44]. In terms of practicality for deployment, the size of the RLS could be made adjustable for attaching to different robots, and the RLS should not cover the joints or motors to prevent restrictions of the robot movement or heat dissipation. For the development in this research, flexible LED light strip was used for the early phase validation of the concept.

2.2. Concept validation

An exploratory experiment was conducted to validate the concept by comparing its effectiveness against a tower light. Its aims are to ascertain whether the robot indicator design concept compared to an industrial tower light increases awareness, reduces workload and improves reaction times for operators. The objectives are to evaluate the performance of participants completing an assembly task when subject to different experimental conditions, measure participants' reaction times to different type of signal lights while observing the robot performing a task, and to measure the visual fixations of participants throughout the task. The experimental parameters were measured with an eye tracker device. The results of this experiment will be used to