On Physical Compatibility of Robots in Human-Robot Collaboration Settings

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***Abstract*—Human-Robot Interaction (HRI) is a multidisciplinary field. It has become essential for robots to work with humans in collaboration and teamwork settings, such as collaborative assembly, where they share tasks in an overlapping workspace. While extensive research is available to ensure successful HRI, primarily focusing on the safety factors, our objective is to provide a comprehensive perspective on robot's compatibility with humans in such settings. Specifically, we highlight the key pillars and elements of Physical Human-Robot Interaction (pHRI) and discuss the valuable metrics for evaluating such systems. To achieve compatibility, we propose that the robot ensure humans' safety, flexibility in tasks, and robustness to changes in the environment. Ultimately, these elements will help assess robots' awareness of humans and surroundings and help increase trustworthiness of robots among human collaborators.**

I. INTRODUCTION

In Collaborative Robots, physical Human-Robot Interaction (pHRI) is an integral part of the tasks and workspace settings. Many factors can affect the systems' ability to complete tasks shared by humans, and robots [1]. Human factors described in [2] summarize the critical human factor issues and provides the design guidelines. A survey [3] examined and provided 42 distinct metrics that are categorized to the object being directly measured. While there are numerous metrics available to measure human-robot interaction performance (e.g., [4]), only a few mechanisms are there to measure these features [5], [6].

In pHRI, the physical compatibility between Human and Robot is the capacity of both to work together without ill effect. Having a good compatibility means it is easy to understand the robot's intentions by the human and human intentions by the robots, simple for human to operate the robot which can help the users feel safe and enhance trust and interest, thus improving the efficiency of use. Compatibility also refers to interoperability between human and robot. The *physical compatibility* of robots in pHRI settings has not been comprehensively studied in the literature, even though it has significance in ensuring a thriving collaboration environment. Therefore, we discuss some perspectives and vital elements of the physical compatibility of robots in human-shared collaborative tasks in shared workspaces.

While the safety of humans in a human-robot interaction setting is extensively studied in manufacturing and industrial application [7], [8], [9], we need to find a way in which safety of the human can be guaranteed when humans and robots are tightly embodied and integral to the task, for instance in collaborative settings where physical contact of robots can occur. According to [10], the safety of humans is divided into physical safety and perceived safety. In the relevant literature, [11], [12], [13], several indices of the severity of an impact are proposed, which can be mapped (through extensive experimental campaigns and statistical correlations) to the probability of causing a certain level of injury. Among these are the Gadd's severity index (GSI), the 3 ms criterion, the viscous injury response (VC), and the thoracic trauma index (TTI), to name a few. The most widely used index in the automotive industry is presently the so-called head injury criterion (HIC). Indeed, the paper [14] extrapolates experimental and simulation data to suggest that any robot, no matter how massive, whose parts are moving with a velocity of up to 2 m/s, would not cause impacts with a HIC larger than ≈ 100, which is similar to what would occur to a person quickly walking and hitting a wall headfirst.

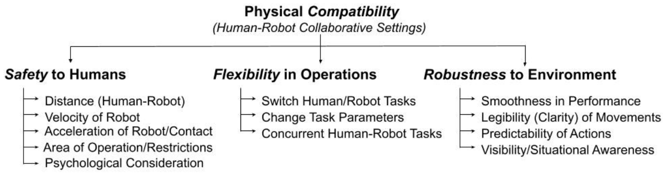

Fig. 1. Key Pillars of Physical Compatibility in Human-Robot Collaboration and Teamwork Settings.

Apart from the safety of humans, the robot's flexibility to tasks and robustness to environments are also essential factors to ensure robot compatibility in realizing successful pHRI tasks. During HRI, robots or humans should be able to move with ease and comfort in each other's workspace. Whereas the robot should also be prepared to be disturbed, it should resume/restart working as the disturbance is removed. Work in [15], [16], [17] addresses the issues of how high-speed robots may move among humans such that the robots complete their tasks efficiently while the humans in the environment feel safe and comfortable. According to these articles, human-aware motion planning [17] will help in completing the task efficiently with less idle time and increased productivity.

As we can see, while there are numerous literature available for safe HRI, most of them belong to industrial applications. Ensuring human safety is one of the most important considerations within the field of human-robot collaboration setting. However, there are other components that need to be considered for obtaining the highest physical compatibility between human and robots. But, studies so far have looked at these different components separately, with different objectives for achieving a safe and successful HRI. In our work, we aim to provide a holistic perspective of physical compatibility by looking at several factors such as safety, flexibility, and robustness into one common assessment and evaluation framework that will ultimately contribute to achieving successful and safe

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pHRI. The framework can be expanded by considering more factors and measures that will benefit the HRI community to adapt to different domains. Therefore, in this paper, we propose three key pillars of the physical compatibility of robots with humans in collaborative settings: safety, flexibility, and robustness, along with their relevant measures. These factors and measures will sufficiently provide an assessment of physical compatibility in pHRI settings.

Figure 1 summarizes the key pillars of compatibility. Here, we presented three factors that we believe are essential to evaluate and assess the physical compatibility of humans and robots. There are measures that can be used to keep the factor checked for each element. Below, we revisit the literature on each of these aspects and provide some key measures in detail. Moving forward, our objective is to arrive at an evaluation scheme and scale with which we can provide an objective assessment of physical compatibility given a robot in a human-interaction setting with shared tasks and shared workspaces.

II. SAFETY OF HUMANS

The safety of humans is of paramount importance in the physical interaction of humans and robots. The standard way to ensure safety is to analyze the distance between the human and robot's point of contact. Once the distance between the human and robot decreases below the distance threshold (safety/separation distance), the velocity of the robot should decrease, or the robot should stop. Thereby, collisions are avoided. The velocity of the robot can depend on the HIC value it generates. Usually, a velocity of 2 m/s is not harmful to humans [14]. We can calculate safety distance on both sides (robot and human) so that the robot can decrease its speed, and the sensor on a human suit will start vibrating (feedback) or make a sound so that humans will know that the robot is near. This way, safety can be assured in the perception of humans or an external observer using objective measures.

Also, human-aware motion planning can ensure that humans are safe when a robot works separately without sharing its workspace. This way, humans will not be disturbed mentally or physically as well as the robot will not need to stop its task. For instance, in [18], the authors provide a measure of Danger Index calculated using the distance, velocity, and inertia measures to use in the robot's global and local motion planning phases. This index was used to ensure that the trajectories generated by robots can be safe and optimal for HRI. Alternatively, one can implement a sampling-based planning approach called Sampling-Based Model Predictive Control (SBMPC), which plans the movement of the robot in a dynamic environment and [15] shows the velocity constraints needed to make sure humans feel comfortable. And the last part is to restrict the operating area of the human if a human is not feeling comfortable or has to do work in the same workspace. Below, we reiterate some safety measures proposed in the literature.

The Safe Distance (SD) formula for safety of the human working with industrial robots is given in the standard EN ISO 13855.

$$SD = K \times T + C \tag{1}$$

SD computes the minimum safety distance from the risk zone. Here, K is the speed of the approaching human collision with the robot (mm/s). T is the robot's follow-up time to stop completely once the brakes are applied, in seconds. C is the additional distance (mm) for safety compliance, that depends on the sensor's capability.

The head injury criterion (HIC) measures the likelihood of head injury arising from an impact.

$$HIC = max_{t_1,t_2}\{(t_2 - t_1).[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt]^{2.5}\} \tag{2}$$

Here, t_1 and t_2 are the initial and final times (in seconds) chosen to maximize HIC, and acceleration a is measured in gs (standard gravity acceleration). The time duration, $t_2 - t_1$, is limited to a maximum value of 36 ms, usually 15 ms. This means that the HIC includes the effects of head acceleration and the duration of the acceleration. Large accelerations may be tolerated for very short times.

Once physical safety and completing the task are ensured, we can look into human perceived/psychological safety. Detecting basic human intentions and developing learn and repeat behavior can help reduce stress and build trust among each other. Preventing physical harm alone, however, does not necessarily translate to stress-free and comfortable interaction [10]. It is important to note that psychological damage, in contrast with physical harm, is not limited to proximal interaction, as it can also be sustained through distal interaction via a remote interface. Therefore, we also include the psychological safety metrics into our safety pillar. Psychological safety is generally analyzed through a questionnaire, but we can also utilize various physiological metrics measured through various sensors such as heart rate, heart rate acceleration, skin conductance response, rate of change of skin conductance, and corrugated muscle response [10]. Initially, we consider basic measures of human state (e.g., heart rate) that can provide strong indications on their psychological situation.

III. FLEXIBILITY IN TASKS/OPERATIONS

Flexibility is another essential aspect of successful pHRI. Flexibility will allow the robot to switch between tasks and restart the task after the disturbance is ended. This will also allow the robot for concurrent movement, leading to less idle time and more productivity. Flexibility allows humans to develop trust in robots. Whenever needed, humans can change the required parameter, and the robot should adapt to it and also predict human intentions so that it can change its decision based on human actions.

In the real world, robots may make decisions that will not align with the human intentions or may need to change the current task of the robot for some reason. For this, humans need authority over the robots so that they can change the decision as well as the task of the robots. The whole purpose of the HRI is to increase the productivity of the team as well as reduce the human workload. To accomplish this primary purpose, we need the robot to work with humans concurrently without making the human or robot come to a stop or hurt each other. For this, we need human-aware algorithms such as dynamic human-aware motion/path planning to reduce the idle time for both and increase productivity by doing the work concurrently. Studies such as in [17] show that having human-aware motion planning in close proximity for human-robot collaborations increases productivity.

Accordingly, we consider the following measures under the pillar of flexibility in operations, devised to ensure adaptations and task flexibility during operations.

- Ability to switch robot's task dynamically through a user interface or natural interaction modalities
- Ability to change the task parameters and settings through a user interface during the pHRI and collaboration
- Ability of the robot to handle concurrent tasks with human through the availability of human-aware algorithms (e.g., human-aware motion planning)

These measures will protect the human operator by giving him/her the ultimate authority in pHRI tasks, and enhance the physical compatibility of the pHRI.

IV. ROBUSTNESS TO ENVIRONMENT

The robustness of robots to changes in the environment is another important aspect of robots' compatibility in HRI. Robots should be able to adapt, learn and repeat behavior so that they can learn from their past and repeat if the task was successful or change its course to do better. When we give the authority to override any decision/task/parameters to humans, the robot needs to adapt to those changes and complete all the tasks smoothly. We already have functions and algorithms which allow the robot to predict human intentions and generate all possible changes that are adjustable in an environment [19].

Studies in [19], [16] used functions that can be used to calculate smoothness. Several dynamical quantities can be minimized across the trajectory to generate smooth motion. Here, legibility means that the human or observer can read the robot's intentions clearly, and predictability means that the robot's action matches the observer/human's inference. Visibility is also vital for the safety and completion of tasks without hindrance from each other. As per the literature, a robot should always remain (at least) within 160° view of the human.

Visibility cost is defined as the angle between the predicted human gaze and the line between the position of the robot end-effector and the human's head. The cost is scaled inversely to the variance of the prediction of the human head pose.

$$C_{visibility}(\xi_r, \hat{x}_h) = \sum_{t=0}^{T} \frac{\angle(O, \mu^h_{head}(t), p^r_{eef}(t))}{\sigma^h_{head}(t)} \tag{3}$$

Here, O is the 3D position of the object with which the human is interacting, $\mu^h_{head}(t)$ and $\sigma^h_{head}(t)$ are the mean and variance of the predicted 3D position of the human head and $p^r_{eef}(t)$ is the 3D end-effector position at time t.

The robot's motion must be legible; that is, it must convey its intent through its trajectory.

$$C_{legibility}(\xi^r) = \frac{\sum_t P(G|\xi^r_{S\to Q_t}) f(t)}{\sum_t f(t)} \tag{4}$$

In the above equation, we replicate the Legibility cost from [20]. $\xi^r_{A\to B}$ is the trajectory from configuration A to configuration B. S denotes the robot's start configuration, G denotes its goal configuration, and Q_t denotes its configuration at time t. $f(t)$ is a weighing function that increases the cost of legibility towards the beginning of the trajectory.

To better decrease the jerkiness of adapted trajectories as well as to even out speed across the execution of the trajectory, we use the sum of squared acceleration of the robot as follows:

$$C_{smooth}(\xi^r) = \sum_{t=0}^{T-2} (\| \frac{d^2}{dt^2} \xi(t) \|^2) \tag{5}$$

Imagine someone knowing that the robot is reaching towards the task 1 out of 3 tasks. Even before the robot has moved, the observer creates an expectation, inferring how the robot will move. We denote this inference function mapping goals to trajectories, as

$$\mathcal{I}_p : \mathcal{G} \to \Xi \tag{6}$$

We formalize predictable motion as a motion for which the trajectory $\xi_{S\to G}$ matches this inference:

$$\mathcal{I}_p(\mathcal{G}) = \xi_{S\to G} \tag{7}$$

V. CONCLUSION

In this paper, we provide key pillars of the physical compatibility of robots with humans, especially in collaborative workspace settings. Compatibility needs to be studied and evaluated even more holistically than just from a safety perspective. However, most studies in the literature on pHRI focus either on the safety of the human inside industrial settings or on predicting human intentions so that robots and humans can work comfortably without harming each other. Moreover, in some tasks, robots may have to come in (intentional) contact with humans and have to complete the task reliably without hurting their human partner. Therefore, we provide some unique views on the physical compatibility of robots and humans in teamwork and shared tasks in shared workspaces. Specifically, we present three pillars of compatibility: safety, flexibility, and robustness. We describe measures of each of these factors and analyze compatibility from different perspectives. Our future work includes developing comprehensive scale, metrics, and assessment schemes to evaluate these features and arrive at a holistic evaluation of physical compatibility in realistic pHRI scenarios such as collaborative assembly tasks. Further, we will analyze compatibility from three perspectives:

1) Robot's perception and assessment of the compatibility.
2) Human's perception and assessment of the compatibility.
3) External observer's perception and assessment of the physical compatibility.

We will investigate the compatibility along these different dimensions and perspectives to help unlock a comprehensive evaluation framework and measures to ensure robot compatibility with humans in collaborative workspaces.

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