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| RESEARCH ARTICLE

Human-Robot Collaboration in Mechatronic Systems: Towards Ergonomic and Safe Mechanical Design

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| ABSTRACT
Collaboration between human and robot is rapidly increasing. The safety trend is moving from 'keep humans out' to 'design for safe and intentional interaction.' In mechatronic systems, how you design your hardware, where components are connected, where the end-effector is, how flexible or how tight everything is, how far apart components are, and where everything goes, is often what determines whether a human-robot collaboration can occur. The paper proposes a design-oriented framework for HRC mechatronic systems. It combines risk thinking and safety-by-design concepts of safety function planning. In this framework, rather than relying on real-world information or experiments, known safety-by-design, robot safety, and body design thinking can be combined into a process. The process can be applied to the requirements phase of design. The proposed design-oriented framework produces verifiable outputs, which can be a combined list of hazards and ergonomics, a relationship between hazards and design changes, and a plan to verify both simulation and documentation-based verification.

| KEYWORDS

Sarodagh, Chromite, Ophiolite, Goshta, Peridotite, Nangarhar, Jalalabad, Afghanistan

| ARTICLE INFORMATION

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1. Introduction
Human-robot collaboration (HRC) is also leading to changes in design and use of mechatronic system designs. Robots are no longer confined to fenced automation cells but are sharing workspaces with human beings. Conventional industrial robots typically maintain a safe distance between humans and technology. In human-robot collaboration, it is required to have safe and continuous close proximity and sometimes even physical contact, such as guiding a robot with one's hand or both working together to transport an object or passing it between human and robot. Thus, there is an emphasis in engineering design that has altered from avoid contact to manage contact [1].

In teams, errors and near-errors occur due to straightforward designs, not complex control systems. Geometric designs that produce points where people can get caught, tools that display sharp edges, heavy arms, poorly located handover points, and the wrong workstation height can result in injury escalation, poor posture, and lowered worker trust levels in the system. A well-considered control system will still be constrained, since the system's design establishes fundamental limits, such as the force that the object can apply, the likelihood of being caught, and the availability of emergency control points [2].

Although there is an increasing number of HRC studies, there is still limited research regarding how people perceive, plan, and learn. Practical knowledge on how to design mechatronic HRC systems, taking into consideration both safety-by-design knowledge and ergonomic knowledge, is divided among ergonomics principles, safety standards, and industry best practices. The above paper fills this research gap, as it presents a framework on how to combine ergonomic thought and safety-by-design knowledge specifically within mechanical design for mechatronic HRC systems. The paper remains at a high level and requires neither specific data nor any other information. The paper presents a specific and useful flow, which can be applied to early CAD activities. The presented area of expertise involves physical collaboration regarding tasks of a generic nature [3][4].

2. Background and key concepts

Human-robot collaboration for mechatronic system designs has a variety of relationships they might have based on how much they share their space and time. There might be situations where humans and robots only share their space without much overlap. There might be situations or steps taken to complete tasks within the same workspace by humans and robots alternately. Advanced levels of collaboration might involve working on the same component or assembly, where the human and the robot collaborate on their respective tasks in a coordinated fashion, and handing over tasks to each other, where they take turns to pass on items to each other with a collective responsibility to keep things steady and on schedule [5].

For human-robot collaboration (HRC), ergonomics refers to how well human beings are compatible with the system. This includes physical aspects such as those related to posture, reach distances, repetition of movements, and force required and contact between the human hand or forearm and the robot while guiding or handing over control. In collaborative activities, dangers may arise from maintaining positions for prolonged periods of time, small forces, and even the rapid pace set by the robot's movements. Another equally important aspect is cognitive compatibility. This is because human beings must be able to interpret what is happening through human-robot collaboration, anticipate robotic movements, and respond accordingly when warned or stopped. This is because if human-robot collaboration acts in unexpected, complex, or inconsistent manners, it is difficult to remain safe [6].

Safety in HRC must be considered from various layers. It commences with good mechanics and incorporates mechatronic safety elements. Typical risks include unintended collision, crushing or being trapped between moving parts and fixed objects, shearing at joints, becoming entangled with equipment or cables, and unintended start-ups during servicing. Safety measures include: reducing speed and force, establishing protective distances with sensors, allowing hand guidance with controlled motion, and utilizing good protective stops and accessible emergency stops. However, from a practical perspective, such safety measures would only prove efficient if the actual machine had low inertias, minimum distances, smooth interaction surfaces wherever necessary, and an arrangement that keeps operator work areas clear and accessible.

Furthermore, recent work from the theory community related to these cyber-physical and digital integration topics can inform human robot collaboration research despite the lack of real-world data. Specifically, a design science approach to framework development transforms the concept of monitor–and-respond, learn–and-adapt into closed-loop control and allows validation on internal consistency rather than real-world testing. This reflects how an HRC research paper may conceptually demonstrate the ergonomic safety benefits of repeated sensing, evaluation, and redesign for a collaborative work environment [7]. Analogously, in an HRC research context but in the nearby realm of manufacturing, the integration of digital twins relates the real-world system with a virtual model of it that can improve predictive understanding, rapid decision-making, and then a balance between autonomy and human control. This analogy applies directly to HRC because then digital twins can be used to simulate human movement and loads, robot paths, and danger conditions prior to selecting a final mechanical design [8]. Lastly, research completed on digital transformation that concentrated upon the concept of IoT sensing and real-time monitoring for predictive analytics upon anomaly detection illustrates the effectiveness of sensor feedback loops and active responses. Applied back upon the HRC research problem, these concepts could represent instrumented workstations that rely on the measurement of unsafe proximity conditions, excessive strain upon the human worker, or deviations from the processing sequence that then drive mechanical design or control system modifications that ensure the ongoing effectiveness and safety of the HRC [9].

3. Problem statement: hazards and ergonomic risk in mechatronic co-design

Designing for operators when designing a robot system requires a combined approach to safety and ergonomic design, rather than a two-part check at a later date. Additionally, when collaborating with a robot, dangers from technology and dangers from human anatomy often correlate to the same design elements: for instance, mounting a robot or designing its end-effector or creating gaps between parts of a robot and nearby pieces of equipment. The system may be safe from a strictly technological perspective but may necessitate operators to stretch or move rapidly or place their hands in awkward positions to complete a task, increasing ergonomic fatigue and dangers of injury. Alternatively, a workstation may be very ergonomic to use but may pose hazards of pinching or crushing [10].

Sources of mechanical hazards in human-robot collaboration (HRC) involve the interaction of energy and shape during robot movement and interaction with objects. The robot's weight distribution and accelerative capabilities impact the severity of a collision. Link and tool geometry determines whether a collision will result in a mere touch or a pinch hazard. Pinch points can arise between neighboring links of a robot's arm, between an arm and a fixture, or between an end-effector and a object. Such hazards increase with the presence of a nearby human within the robot's environment. Robot tools introduce additional hazards due to their capability of generating a large amount of force on sharp edges, rotating components, hot surfaces, and cutting surfaces even when the robot is moving at a low velocity [11].

The ergonomic hazards involved in teamwork with a robot include those associated with adjusting their body to the robot and timing. If the contact area is out of reach, too high, or in the wrong direction, the human increases their shoulder, spinal, or wrist exposure, and these positions get repeated numerous times. If there is a need for constant guiding force and/or unusual gripping shapes, contact pressures and/or muscular fatigue will build up, although the force levels are low. Psychological elements include those involved when the robot's purpose is unclear and humans may hold back, overcorrect, or stop while waiting for the robot to complete its action [12].

Also, the presence of mechatronics surely increases the complexities involved in safety and comfort. A safe system could be erring on the side of caution, causing the robot system to move slowly due to frequent stops, which can increase human effort while also causing people to take long workarounds in order to benefit from the system. Aggressive optimization, on the other hand, limits the space available for unexpected human motions while using the system, which causes a problem in system design in ensuring that all these aspects are considered in relation to the design of the system itself, so it remains safe while also appearing ergonomically natural.

4. Proposed framework: the "ErgoSafe HRC Design Loop"

ErgoSafe HRC Design Loop is a structured process to design human-robot collaboration systems when there are little actual information and experimental knowledge. The intention is to introduce ideas of ergonomic and safety-by-design thinking early on when there is still time to modify machine parts and designs. The design loop views the human-robot collaboration system as a human-machine-environment entity where danger, comfort, predictability, and performance are simultaneously derived from both machine parts and mechatronic functionality. The design process is no longer focused on what capabilities the robot possesses but instead begins with the collaboration task itself to develop requirements and plans to gain evidence based on this predefined task.

The first phase describes the task and how the collaboration will occur so that the design requirements can be formulated. The engineering team describes what the person does, what the robot does, and what they do in common. They also pay particular attention to whether there is contact or only accidental contact. This phase also describes where the work is to be done, how much of the workspace should be involved, how components might be represented differently, and how much the people using the system might know, for example, how much their body size might be. By giving names to these assumptions, the design prevents "hidden" requirements from developing, which tend to appear later when safety or ergonomic problems come up.

The second level formulates ergonomic requirements as design constraints that the designer can then use when planning the layout and in early CAD systems. Again, the goal is not to optimize ergonomic ratings, but to express human requirements as constraints and goals that influence the part geometry. A set of preferred activity areas are specified by the designer, including a good handover region that preferably stays in a location accessible by sight and reach, and avoids locations that involve reaching overhead, wrists, or bending the torso. Some force requirements are also considered generally, especially when guiding a part by hand or together with another operator or when using tools, because smaller to moderate force levels applied repeatedly might cause fatigue if executed poorly and under time pressure. Here, the notion is that designers will use ergonomics as a design constraint that the design will satisfy.

The third stage is concerned with safety-by-design, where design options for machinery are assessed to mitigate risk at source. The preferred method involves intrinsic safety, where risks of pinch and trapping are eliminated or decreased by considered clearance design, avoided sharp edges, protection of moving machinery, and link and join design to decrease the risk of snags and crushing. The importance of energy control by machinery design is also shown, where the reduction of inertia and force peaks can significantly improve safety without any control measures. The objective can be achieved by minimizing weight, proper placement of ponderous components, elastic components if necessary, and tool design to distribute pressures. The structure considers end-effectors as a source of risks, where injuries to people are often caused by tool design rather than robot arms, especially where cutting, clamping, and rotation are involved.

The fourth level links safety functions of mechatronics to mechanical and ergonomic requirements specified previously. It ensures that decisions regarding sensing and controls are not made in a vacuum. For instance, protective separation, speed and force limits, hand guiding, and protective stops are all dependent on a mechanical system and its ergonomic requirements. For instance, separating functionality will be feasible only if sensors are able to view the interaction area and do not provide blind spots through which human movement is likely to pass. Speed and force limits would be appropriate if there is a mechanical system with low inertia contact characteristics because setting control limits may not be adequate to prevent high pressure in a tight spot. Finally, emergency and protective stop controls should be placed in a location from which accessibility is maintained even when collaborating, or these will merely be regulatory requirements instead of solutions to actual hazards. The design cycle links safety and product functionality to ensure practical solutions to identified hazards.

Finally, this step produces a plan for verification that can be referenced in future simulation, documents, and structured reviews even in the absence of immediate experiment data. This approach is centered on having adequate evidence through design records like a combined hazard/ergonomics log, a hazard to mechanical design control/safety functions relationship, and a hierarchy of acceptance criteria based on original task notions. CAD-based clearance checks, risk assessment organization, and failure mode thinking can be planned to provide a distinct path between design and requirements. This approach will not eliminate the need for physical validation but will provide a safer and more ergonomic design at an earlier stage with a reduced risk of basic problems being exposed by late testing that would then require costly redesign efforts.

Concluding, “ErgoSafe HRC Design Loop” is a useful and verifiable approach to integrate ergonomics and safety aspects into mechanical design decisions of collaborative mechatronic systems. This technique is valuable because it considers embodiment, control, and human aspects as a single design problem and also develops support documentation for design decisions required in later compliance or certification activities.

5. Design guidelines for ergonomic and safe HRC cells

Starting to make safe human-robot interaction involves contact-aware shapes. Most of the larger hazards exist where machine components intersect with people. Design link profiles and joint enclosures to eliminate hard edges and corners where people can be squeezed or pushed. Curves of contact surfaces can help prevent pressure concentrations. In addition, design to eliminate locations where a hand or fingers could be pinched between moving machinery and a stationary object, and between an end-effector and a fixture. "If hazards can’t be abated, make them visible and hard to reach rather than relying on warning signs."

Energy management is the second area, since the intensity of a collision and the quality of a planned touch are both functions of the amount of kinetic energy the system can supply, and how it is delivered. Reducing effective inertia, peak accelerations, and mechanical stiffness can improve both safety and quality. What this means in practice is using lightweight components in the links where possible, reducing overhang and wrist mass, and selecting tools that distribute the contact force rather than concentrating it in small areas or points. It is important to use compliance thoughtfully, since excessive amounts of it can make the system unruly, effort-full, and tricky to use by people. Instead, the goal is to achieve controlled amounts of compliance to dampen shocks, reduce peak forces, yet maintain predictability of motion and stability of handovers.

Good workspace design and a clear area to "hand over" between the operator and the robot impact standing and reach effectiveness, repetition rate, and the level of trust between the operator and the system. "Handing over" to the robot should be accomplished from a consistent area that can be conveniently accessed without lifting the shoulders, twisting the wrists, and bending the body. A consistent location for repeatable "handing over" also improves safety, as it eliminates last-minute changes and keeps hands out of danger zones. A clear line of sight between the operator and the robot, allowing the operator to see the action the robot intends without much head or body movement, and predictable motion of the robot to avoid sudden surprises and dangerous rapid reaches, are other improvements the design will make.

Maintainability should be integrated into mechanical and safe design and not left to last. Servicing typically involves awkward positions, proximity to dangers, and time pressures, and is, therefore, a potentially unsafe phase of a system’s entire life cycle. Lockout and access of covers and access panels, and tool change interfaces should be designed for easy lockout and access, and should not have wire routings that tend to snag or connectors that tend to go into the wrong places. Design features that assist in safe use and encourage comfort and safety in collaboration can be achieved by usability features built into mechanical design and pointing out “where to put hands.”

6. Discussion: tradeoffs, limitations, and research gaps

Designing human-robot collaborations for mechatronic systems involves weighing objectives that are strongly coupled, and perhaps even conflicting, because of the nature of the robot itself. A more flexible and lighter robot could be achieved, for example, and thus be safer, but at the same time could reduce the positioning accuracy, aggravate the vibrations, or exhibit a springy motion about which less can be predicted. Similarly, a robot carefully set for high safety factors, potentially resulting in slowness and frequent stops, may theoretically reduce the probability of injuries, but pragmatically could slow down entire production cycles and demoralize human operators, potentially resulting in unsafe workarounds. There is a need for a good balance between robust engineering for mechanical safety, ergonomic design, and appropriate safety engineering to avoid a dependence on human behavior assumptions and flawless sensing.

The only limitation of this paper is that the proposed conceptual tool lacks any experiment or specific ergonomic assessment at a particular site. The proposed tool could aid decision-making and forge traceable design documentation, but actual use should incorporate simulation, pilot, and then several rounds of optimization according to actual operator use. Some key gaps of research would be to assess ergonomic performance for dynamic team work, to develop multi-objective optimization techniques for safety, fatigue, and efficiency collectively, and to formalize the body of evidence to relate mechanical design to safety and certification.

7. Conclusion

Collaboration between humans and robots revolutionized the fundamental safety concept in mechatronic systems. Rather, we moved from the practice of maintaining a distance between robots and human workers to one where we maintain constant, deliberate proximity while sharing work. In this relationship, the comfort of the workers or the potential to be hurt by them depends solely on the machine's design parameters, including the forms of the links, the end-effector, the gaps, the complexity of the system, or the areas where both workers and robots interact. Here, important problems arise late in teamwork, such as pinch points, close handoff points, unpredictable contacts, and difficulty in accessing emergencies.

The paper introduces the "ErgoSafe HRC Design Loop." This is a mechanical design method that combines ergonomics considerations, risk reduction, and safety functionality in a structured and traceable process flow. This can even be applied when no actual data or testing is available in the process. It generates easily auditable documents – such as a combined hazard and ergonomics register, a hazard-to-design change mappings map, and a verification plan based on documentation – that assist engineers in making informed trade-offs among safety, ergonomics, and functionality in the early stages of designing HRC mechanisms. This generates more practical HRC mechanisms by aligning the mechanical designs with human and safety needs.

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