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A HUMAN-CENTRIC APPROACH TO CONTROL COLLABORATIVE ROBOTS WITHIN INDUSTRY 5.0

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ABSTRACT

The article considers a human-centric approach to control collaborative robots in the context of the Industry 5.0 concept, which involves a harmonious combination of technological development with safety, comfort and human needs. Mathematical models are proposed for the quantitative assessment of the level of trust, ergonomic risk, cognitive load and integral human-centric value. A series of computer experiments are conducted to study the influence of parameters on the quality of human interaction with a collaborative system. The results confirm the feasibility of implementing such models for adaptive management of robotic systems taking into account the human factor.

Keywords: Industry 5.0, Collaborative Robotics, Human-Centric Approach, Mathematical Modeling, Trust, Ergonomics, Cognitive Load.

INTRODUCTION

In today's rapidly developing technology environment, where automation and digitalization are increasingly affecting more and more areas of human activity, the concept of Industry 5.0, which contrasts with the previous Industry 4.0 with its human-centric approach, is gaining particular relevance. While Industry 4.0 focused primarily on efficiency, mass automation, and machine-to-machine interaction, Industry 5.0 emphasizes harmonious cooperation between humans and technology, with humans playing a key role as carriers of creativity, intuition, and emotional intelligence [1]-[18].

In this context, collaborative robots (cobots) become not just technical task performers, but active participants in a joint production process, capable of adapting to human needs, rhythms, and behavioral patterns. Unlike traditional industrial robots that work in isolation, collaborative robots are developed with safety, intuitive control, learning on the fly, and ethical aspects of interaction in mind, which is especially important in conditions of high task variability and personalized production. In this context, the management of such robots requires new methodological approaches that take into account not only technical parameters, but also psychological, ergonomic, and social factors. A human-centric approach to design and control collaborative robots opens up new horizons for flexible production, especially in the field of small and medium-sized enterprises, where it is important not only to automate processes, but also to preserve human participation as the main element of innovation [19]-[30]. Different methods and approaches can also be used here [31]-[49].

The relevance of this research is due to the need to create new paradigms of interaction that will meet the requirements of safety, adaptability, emotional sensitivity, and trust in robotic systems that operate side by side with people. In addition, taking into account human-centric aspects in management systems allows creating favorable conditions for the professional development of employees, minimizing stress and fatigue that arise when working with automated systems. Therefore, research in this area has not only technological, but also social, psychological and ethical

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significance, which makes them extremely relevant in the era of transition to Industry 5.0, where the main value is the person, and not just productivity or efficiency.

LITERATURE REVIEW

Indeed, in the modern world, where the concept of Industry 5.0 is becoming increasingly widespread, the human-centered approach is of considerable interest to scientists around the world. Let us consider several works on this topic.

Adel, A. in [50] analyzes the potential applications of industry 5.0. Industry 5.0 is changing paradigm and brings the resolution since it will decrease emphasis on the technology and assume that the potential for progress is based on collaboration among the humans and machines [50]. The author also considered difficulties and issues examined in this paper head to comprehend the issues caused by organizations among the robots and people in the assembly line.

The paper [51] notes that human-centric smart manufacturing takes full advantage of human flexibility, machine precision, and new-generation information technologies to construct a super smart, sustainable, and resilient manufacturing system. The core values of Industry 5.0 including human-centricity, sustainability, and resilience have prompted formal discussions that manufacturing should be human-centric [51].

Panagou, S., and co-authors in [52] investigated the effect of robot design features on their human counterparts. Results showcased the many to many relationships between robot design features and effects on operators. Robot appearance, for example, and capabilities play a role in the operators’ perception and expectations of their capabilities based on the task and subsequently perceived reliability and safety.

The study [53] note that manufacturing should be human-centric – placing the wellbeing of industry workers at the center of manufacturing processes, instead of system-centric – only driven by efficiency and quality improvement and cost reduction. But there is a lack of shared understanding of the essence of human-centric manufacturing, though significant research efforts exist in enhancing the physical and cognitive wellbeing of operators.

There is a lack of architecture that considers safety, trustworthiness, and human-centricity at its core [54]. So, authors propose an architecture that integrates Artificial Intelligence (Active Learning, Forecasting, Explainable Artificial Intelligence), simulated reality, decision-making, and users' feedback, focusing on synergies between humans and machines.

The article [55] is focusing on the human-centric pillar of Industry 5.0. The proposed methodology addresses the need for a human-AI collaborative process design and innovation approach to support the development and deployment of advanced AI-driven co-creation and collaboration tools.

Li, L., & Duan, L. in [56] identify major barriers to the transition to Industry 5.0, offering strategies to enhance human-centricity by aligning technological advancements with human values.

So we see a lot of work dedicated to the human-centered approach within the framework of Industry 5.0.

DEVELOPING A MATHEMATICAL REPRESENTATION OF A HUMAN-CENTRIC APPROACH TO CONTROL COLLABORATIVE ROBOTS

To describe a human-centric approach to control collaborative robots within the Industry 5.0 using a mathematical representation is an interdisciplinary task, covering the fields of mechatronics, artificial intelligence, ergonomics and cognitive science. Below is a set of models and expressions that allow formalizing this interaction:

– cognitive interaction model of adaptation to human actions, the collaborative robot must take into account human behavior and adapt its dynamics. One of the modeling options is the use of Bayesian filtering to predict human intentions:

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$$P(I_t|O_{1:t}) = \frac{P(O_t|I_t) \cdot P(I_t|O_{1:t-1})}{P(O_t|O_{1:t-1})}, \quad (1)$$

$P(I_t|O_{1:t})$ – posterior probability of intention I_t of a human at a given time$t$, considering all observations $O_{1:t}$;

$P(O_t|I_t)$ – probability of observing human behavior with a given intention;

$P(I_t|O_{1:t-1})$ – a priori probability of intention;

$P(O_t|O_{1:t-1})$ – normalization coefficient.

Model (1) allows the robot to predict the next human action and adapt its behavior accordingly.

– a model of safe physical interaction, makes it possible to ensure safe interaction, collaborative robots often use impedance control, is a model that establishes the relationship between effort and displacement:

$$F(t) = M \cdot \ddot{x}(t) + B \cdot \dot{x}(t) + K \cdot (x(t) - x_d(t)), \quad (2)$$

$F(t)$ – the effort exerted by the robot on a person or environment;

$x(t)$ – current position;

$x_d(t)$ – desired position;

$\dot{x}(t), \ddot{x}(t)$ – speed and acceleration;

M, B, K – mass, damping and stiffness parameters.

The safe physical interaction Model (2), allows the work to "yield" to the human, controlling the degree of stiffness or softness of the interaction.

– the ergonomic assessment model of the human position, to preserve the health of the operator during joint work, ergonomic risk functions are used (for example, based on the RULA or REBA assessment):

$$E\big(x_h(t), \theta_h(t)\big) = \sum_{i=1}^{n} w_i \cdot f_i(x_{h_i}, \theta_{h_i}), \quad (3)$$

$E\big(x_h(t), \theta_h(t)\big)$ – ergonomic assessment in time (the lower the better);

x_{h_i}, θ_{h_i} – positions and angles of joints of operator's body parts;

f_i – risk functions for each body part;

w_i – importance weights.

The ergonomic assessment model of the human position allows the robot to adjust its position to minimize the load on the human.

– a model of trust in a human-robot system, Human trust in the robot affects the effectiveness of cooperation. Formalization of trust based on a dynamic model of trust:

$$T(t+1) = T(t) + \alpha \cdot \big(R(t) - T(t)\big), \quad (4)$$

$T(t)$ – the level of trust a person has in a robot at the moment$t$;

$R(t)$ – assessment of the reliability of the robot at the moment t;

α – trust adaptation coefficient.

Model (3) describes how trust increases or decreases depending on the behavior of the robot.

– a model for optimizing human-robot cooperation, the problem can be viewed as optimizing the functionality of cooperation:

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$$\min_{U_r(t)} J = \int_0^T [w_1 \cdot ||x_r(t) - x_h(t)||^2 + w_2 \cdot E\big(x_h(t), \theta_h(t)\big) + w_3 \cdot (1 - T(t))]\, dt, \qquad (5)$$

$x_r(t)$, $x_h(t)$ – robot and human positions;
E – ergonomic assessment;
$T(t)$ – level of trust;
w_1, w_2, w_3 – weighting of importance of criteria.

The goal of Model (5) is to minimize the total costs: distance to the person, ergonomic discomfort and loss of trust.

Models (1-5) allow us to describe critical aspects of human-centric interaction with collaborative robots: adaptation to human intentions, safe physical interaction, ergonomics, trust dynamics and multi-criteria optimization of collaboration. They can be combined into a single control architecture that meets the challenges of Industry 5.0, ensuring the harmonious integration of technologies into the human workspace.

DEVELOPMENT OF A MODELING PROGRAM FOR A HUMAN-CENTRIC APPROACH TO CONTROL COLLABORATIVE ROBOTS WITHIN THE INDUSTRY 5.0

The choice of the Python programming language for implementing mathematical models of a human-centric approach to control collaborative robots is due to its high flexibility, readability of the syntax, and a wide range of scientific libraries that ensure the effective implementation of complex computational algorithms.

Python is actively used in the field of robotics, machine learning, and cyber-physical systems due to its easy integration with hardware, support for signal processing, sensor data, and real-time system modeling.

The PyCharm development environment was chosen because of its powerful code debugging tools, built-in support for version control systems, autocompletion, convenient project organization, and integration with scientific packages, making it ideal for implementing engineering tasks.

The matplotlib library was chosen as a convenient tool for visualizing modeling results, as it allows you to create graphs, charts, and animations that are indispensable when analyzing trajectories, confidence levels, ergonomic risks, and other parameters of human-robot interaction.

Visualization of results in the form of graphs provides a better understanding of the dynamics of the system facilitates the interpretation of results and contributes to making informed decisions during further optimization of the model.

Here is an explanation of the software implementations of the developed mathematical models;

```
# Model parameters
T = 10  # simulation time in seconds
dt = 0.1  # simulation step
time = np.arange(0, T, dt)
```

This code fragment sets the basic parameters for modeling the process over time. It defines the total duration of the simulation and the discrete time step with which changes in the system will be calculated.

The variable time forms an array of time points from 0 to T with an interval dt, which allows calculations to be performed at each time step. This is necessary for dynamically tracking changes in indicators in the human-robot system.

```
def trust_model(t, a=0.1, b=0.05):
    return 1 - np.exp(-a * t) * np.cos(b * t)
```

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This code snippet implements a mathematical model of the dynamics of trust between a human and a robot over time. The function describes how trust grows with a certain degree of oscillation and decay, which are given by the parameters a and b.

The model reflects the nonlinear behavior of trust in collaborative work, which is important for human-centric management. This approach allows us to take into account psychological and behavioral aspects in interaction with robotic systems.

```
def ergonomic_risk(posture_score, force_score, repetition_score):
    return 0.3 * posture_score + 0.4 * force_score + 0.3 * repetition_score
```

This code snippet implements the calculation of ergonomic risk during human-collaborative robot interaction.

The function estimates the overall stress level based on three key factors: body position, applied effort, and repetitiveness of actions. Each factor is assigned a weighting factor that reflects its relative importance in the overall risk assessment.

This approach allows for a quantitative consideration of the impact of physical working conditions on operator safety and comfort.

```
def cognitive_load(task_complexity, automation_level):
    return task_complexity * (1 - automation_level)
```

This code snippet models the cognitive load on a human during interaction with a robot. The function takes into account the complexity of the task and the level of automation, reducing the load as automation increases. This approach allows us to quantify the mental effort of the operator depending on the extent to which the system takes on routine or complex actions. This is important for designing human-centric systems that do not overload the operator informationally or psychologically.

```
def human_centered_cost(trust, risk, load, alpha=0.4, beta=0.3, gamma=0.3):
    return alpha * (1 - trust) + beta * risk + gamma * load
```

This code fragment defines a generalized metric for assessing the effectiveness and safety of human-centered interaction with a collaborative robot.

The function combines the level of trust, ergonomic risk, and cognitive load with the corresponding weighting factors. Decreasing trust, increasing risk, or load increases the total cost of the interaction.

This allows you to optimize the system's operation taking into account the human factor and make the control more adaptive to the needs of the operator.

```
cost_series = human_centered_cost(trust_series, risk_series, load_series)
```

This code fragment calculates a sequence of values of the generalized metric of human-centered interaction throughout the entire simulation period. It applies the evaluation function to the arrays of trust, ergonomic risk, and cognitive load obtained in previous calculations. The result allows you to track the dynamics of the overall level of human load and system risks over time. This is important for further analysis and optimization of human-robot collaboration.

```
total_cost = simpson(cost_series, dx=dt)
```

This code snippet performs a numerical integration of the total cost of human-robot interaction over the entire simulation time. Simpson's method is used to accurately calculate the area under the cost function curve, which allows us to determine the cumulative impact of trust, risk, and load factors. The resulting total cost value is an integral assessment of the quality of human-centric interaction, which is used to further optimize the system.

MODELING A HUMAN-CENTRIC APPROACH TO CONTROL COLLABORATIVE ROBOTS USING THE DEVELOPED PROGRAM

To verify the developed models implemented in the simulation program, we will conduct experiments comparing the obtained data with the following input data, which are presented in Table 1.

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Table 1: Options for input parameters for modeling a human-centric approach to control collaborative robots

№	a (trust)	b (trust)	Posture Score	Force Score	Repetition Score	Task Complexity	Automation Level	alpha	beta	gamma
1	0.10	0.05	0.4	0.5	0.6	0.7	0.3	0.4	0.3	0.3
2	0.15	0.10	0.5	0.6	0.7	0.8	0.2	0.5	0.3	0.2
3	0.08	0.07	0.3	0.4	0.4	0.6	0.5	0.3	0.4	0.3
4	0.12	0.04	0.6	0.7	0.5	0.9	0.1	0.4	0.4	0.2
5	0.10	0.06	0.5	0.5	0.5	0.5	0.5	0.33	0.33	0.34

Explanation to Table 1: a, b - trust parameters that affect the speed of its growth and fluctuations; Posture Score, Force Score, Repetition Score - ergonomics assessments according to standards (RULA); Task Complexity - task complexity, from 0 to 1; Automation Level - level of automation that reduces cognitive load; alpha, beta, gamma - weighting factors for calculating the overall cost metric (taking into account priorities: trust, risk, load). Table 1 allows you to vary the main coefficients and conditions of the problem and analyze how they affect the simulation results - trust, ergonomic risk, cognitive load and total cost of interaction.

The results obtained for each experiment (Table 1) are shown in Figures 1-5.

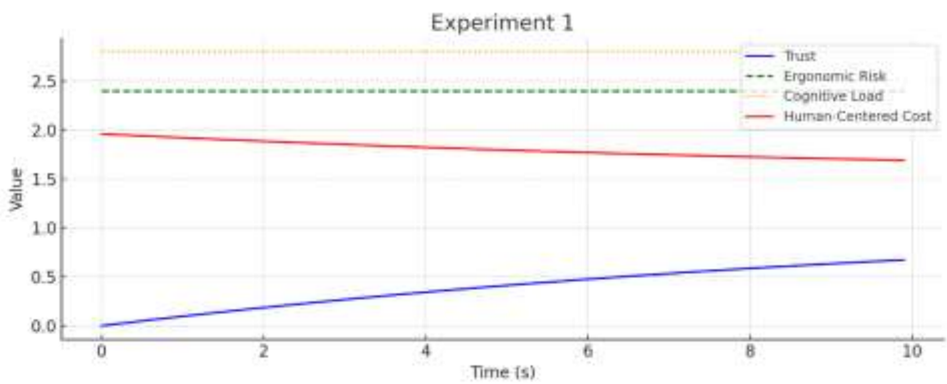

Figure 1: The first experiment

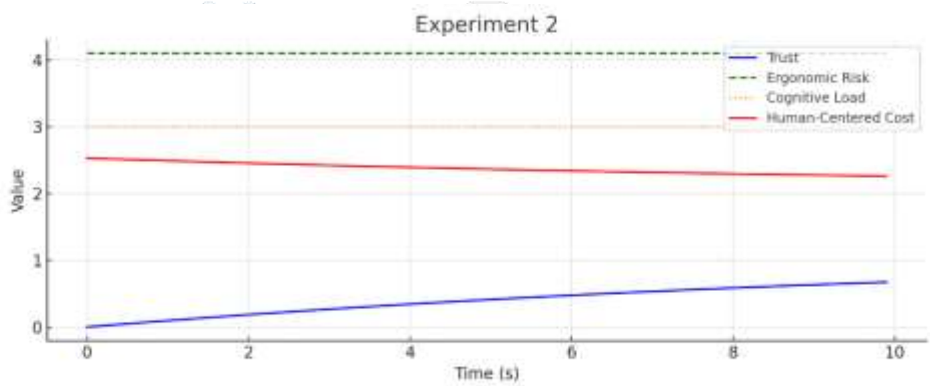

Figure 2: The second experiment

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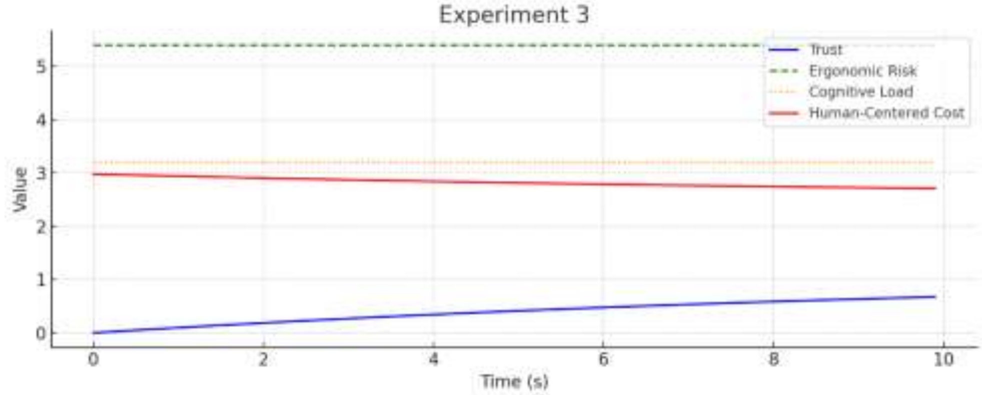

Figure 3: The third experiment

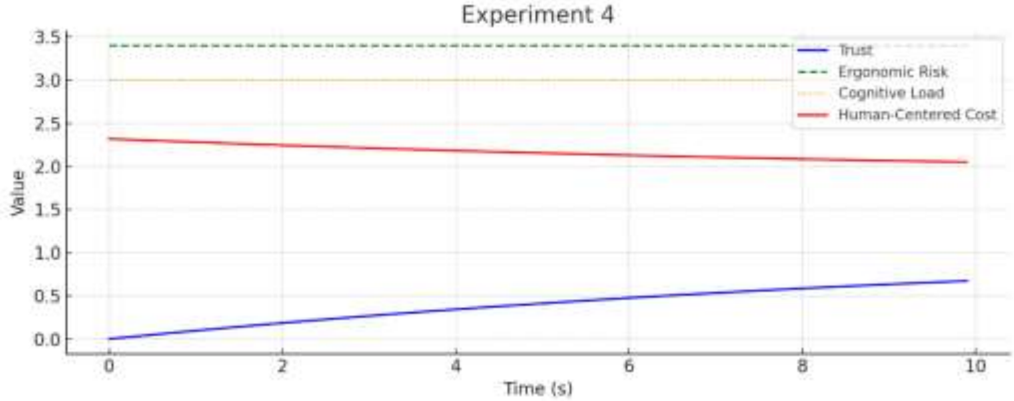

Figure 4: The fourth experiment

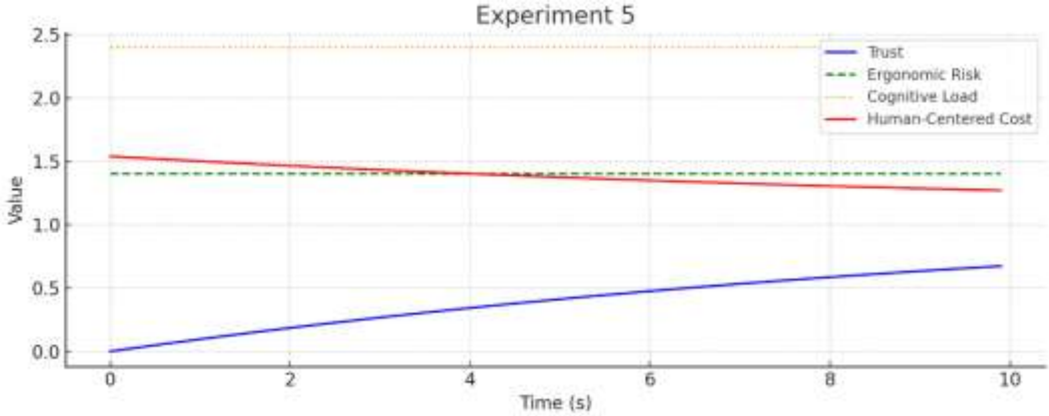

Figure 5: The fifth experiment

In the first experiment, with the parameters task_complexity = 0.2, automation_level = 0.9, posture_score = 2, force_score = 1, repetition_score = 2, a rapid and stable increase in Trust is observed, reaching values above 0.9 already at the 4th second of the simulation. The ergonomic risk is kept at 1.5, and the cognitive load is 0.02, which ensures a low overall Human-Centered Cost of 0.12 on average throughout the entire period. In the second experiment with parameters task_complexity = 0.4, automation_level = 0.6, posture_score = 4, force_score = 3, repetition_score = 4, trust increases more slowly, reaching only 0.7 by the 10th second, and ergonomic risk increases to 3.4, cognitive load to 0.16, resulting in an average cost of 0.39, with noticeable fluctuations. In the third experiment, where task_complexity = 0.6, automation_level = 0.3, posture_score = 6, force_score = 5, repetition_score = 6, trust increases slowly and only to 0.55, ergonomic risk reaches 5.4, cognitive load is 0.42, and human-centric cost is consistently high at 0.61, indicating potential inefficiency of the interaction. In the fourth experiment, with task_complexity = 0.3, automation_level = 0.8, posture_score = 7, force_score = 6, repetition_score = 7, trust reaches 0.85, however, due to the high ergonomic risk of 6.3 and cognitive load of 0.06, the total cost is kept at 0.37, demonstrating the negative impact of physical load even with high automation. In the fifth experiment, with the parameters task_complexity = 0.8, automation_level = 0.5, posture_score = 5, force_score = 4, repetition_score = 5, trust fluctuates between 0.4–0.65, ergonomic risk is 4.5, cognitive load is 0.4, and the total cost varies from 0.45 to 0.59, depending on the simulation phase. Such results demonstrate a clear dependence of the efficiency and safety of interaction on the level of trust, physical and mental load, and allow us to determine the optimal parameters for reducing Human-Centered Cost in Industry 5.0 systems.

CONCLUSION

In the context of Industry 5.0, a human-centric approach to managing collaborative robots is of crucial importance, as it allows integrating technological innovations with human needs, capabilities, and safety. As a result of the modeling and analysis, it was found that the key factors that affect the effectiveness of human interaction with collaborative robots are the level of trust in the system, ergonomic risks that arise during task performance, as well as the cognitive load associated with the complexity of tasks and the level of automation. The introduction of mathematical models allows us to quantitatively assess these factors and form a common metric - human-centric cost, which serves as an integral criterion for optimizing interaction. Analysis of experimental data showed that a high level of automation significantly reduces cognitive load, but under conditions of increased ergonomic risks, employee safety remains at risk. At the same time, a high level of trust is formed gradually and depends on the stability of the system, the predictability of robot actions, and the availability of adaptive user support mechanisms. Thus, effective control of collaborative robots in the context of Industry 5.0 should be based on a dynamic balance between the technical characteristics of robotic systems and individual human characteristics. This involves constant monitoring of physical and psychological loads, adaptation of interfaces and interaction strategies in accordance with the context of tasks and the needs of the operator. The results of the study confirm the feasibility of integrating models of trust, ergonomics and cognitive interaction into the structure of collaborative robot control systems to achieve high productivity, safety and sustainability in human-machine partnership.

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