DEI DOCTORAL RESEARCH SEMINAR

February 9th, Bari

CONTROL IN HUMAN-ROBOT COLLABORATION: A SAFE, ERGONOMIC, AND EFFICIENT TRAJECTORY PLANNING

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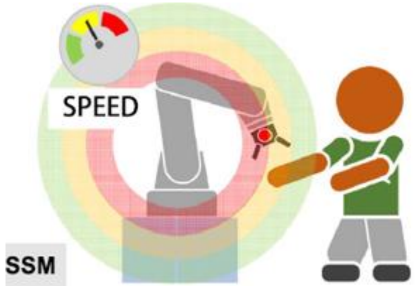
INTRODUCTION
SURVEY
TRENDS AND CHALLENGES
TRAJECTORY PLANNING
CONCLUSIONS

INTRODUCTION



RESEARCH TOPIC

Human-robot collaboration (HRC) in the manufacturing scenario

KEYWORDS

- **Industry 4.0** ➡ production and business management framework that aims at digitizing and automating production processes
- **Collaborative robotics** or **Cobotics** ➡ key enabling technology that has made Industry 4.0 a concrete reality and fundamental pillar of the next revolution, the so-called Industry 5.0
- **Cobots** ➡ specific robots that co-exist in the same environment together with humans, ensuring safety and/or efficiency, in contrast to traditional robots that predominantly work independently from humans and often reside in a cage

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INTRODUCTION

COBOTS’ ADVANTAGES

- Improved ergonomics and employee wellbeing
- Increased profitability and productivity
- Highest quality
- Optimal flexibility
- Pinpoint accuracy
- Reduced downtime of the system
- Suitability for Small-Scale and Mid-Scale

MAIN FOCUS

- Cobots focus on **repetitive tasks** to help workers concentrate on tasks that require problem-solving skills
- Cobots are appropriate for complex and **dangerous** applications

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INTRODUCTION

APPLICATIONS [1-3]

- Assembly processes (i.e., screw driving, nut driving, and part fitting)
- Material handling (i.e., packaging, palletizing, and kitting)
- Material removal (i.e., grinding, milling, and drilling)
- Finishing processes (i.e., polishing, buffing, and sanding)
- Welding
- Quality inspection
- Machine tending

SECTORS

- Automotive
- Electronics
- Agriculture and food processing
- Logistics
- Metalwork
- Healthcare (sanitization and inventory to prevent and reduce the spread of infectious diseases, bacteria, and viruses like COVID-19)

[1]: “Universal Robots website,” https://www.universal-robots.com/, accessed: 2021-07-29
[2]: “Rethink Robotics website,” https://www.universal-robots.com/, accessed: 2021-07-29
[3]: “Omron website,” https://www.universal-robots.com/, accessed: 2021-07-29

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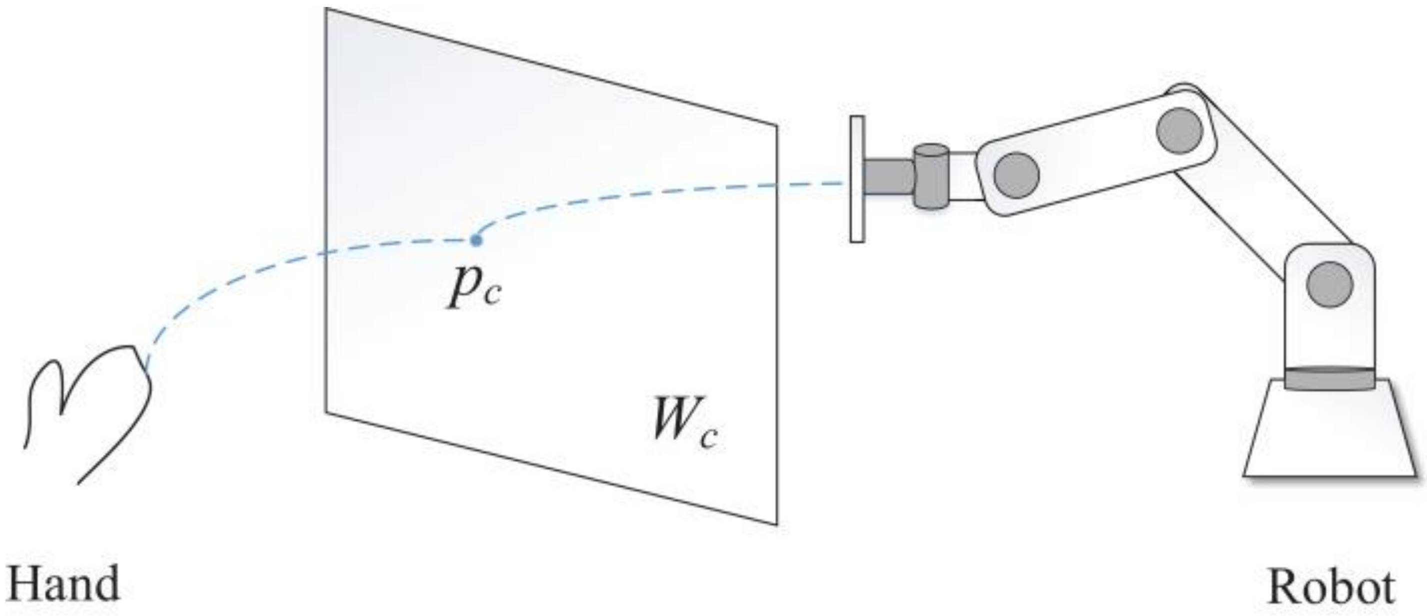
INTRODUCTION

OUTLINE

- Survey on HRC control techniques
- Trends and challenges in HRC control for manufacturing
- Trajectory planning for a safe, ergonomic, and efficient HRC



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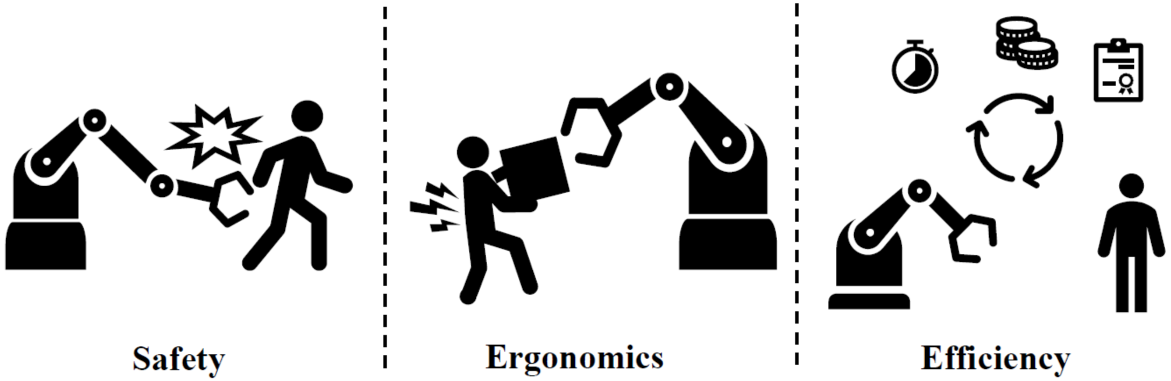
SURVEY ON HRC CONTROL TECHNIQUES

FOCUS

- Systematic review [4-5] of the **control techniques** used in collaborative robotics
- Classification of the most relevant and recent works according to the **three key objectives** of HRC in the manufacturing scenario that are **safety**, **ergonomics**, and **efficiency**



[4]: Proia, Silvia, et al. "A Literature Review on Control Techniques for Collaborative Robotics in Industrial Applications." 2021 IEEE 17th International Conference on Automation Science and Engineering (CASE). IEEE, 2021.

[5]: Proia, Silvia, et al. "Control Techniques for Safe, Ergonomic, and Efficient Human-Robot Collaboration in the Digital Industry: A Survey." IEEE Transactions on Automation Science and Engineering (2021).

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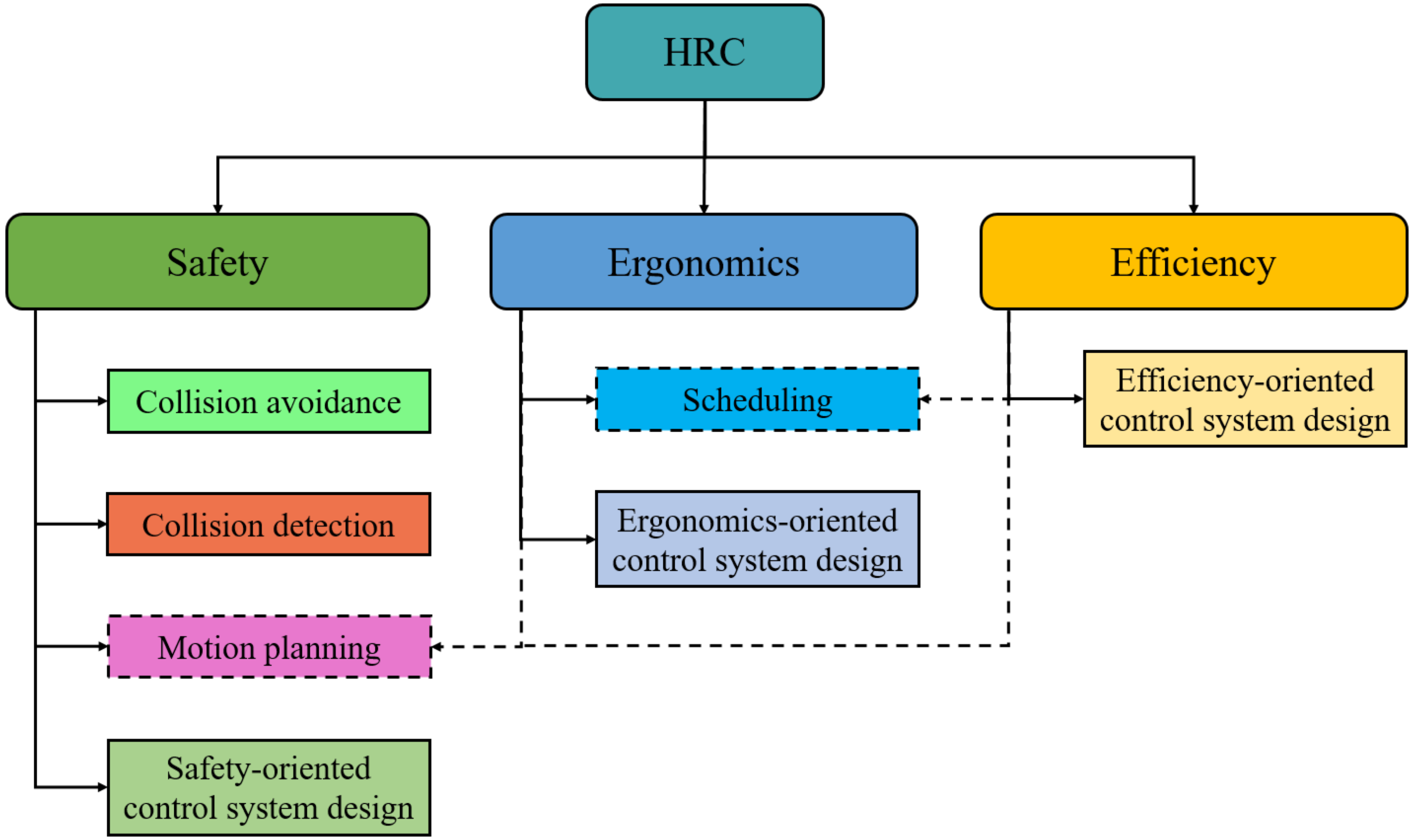
SURVEY ON HRC CONTROL TECHNIQUES

STRUCTURE [4-5]

Classification of the works by **target**, and then by type of addressed **control problem** related to the specific target in presence or absence of optimization



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SURVEY ON HRC CONTROL TECHNIQUES

SEARCH CRITERIA AND PAPER OUTLETS [5]

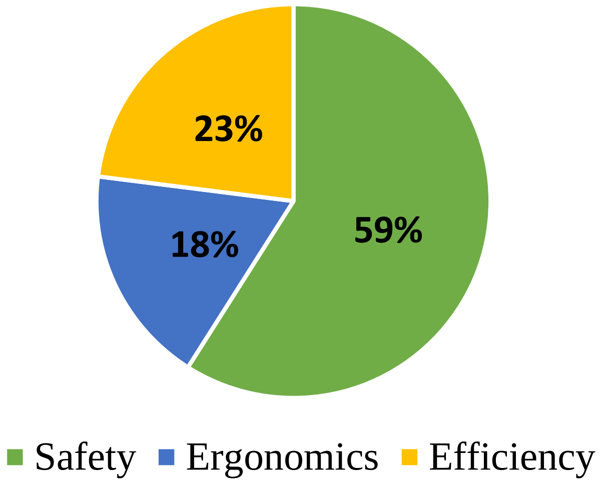
IEEE conference papers
TITLE-ABS-KEY: (*cobots OR (collaborative robotics) OR (human-robot collaboration) OR (human-robot cooperation)) AND control*
YEARS: From 2017 onwards
N PAPERS FOUND: 907
18 papers

SCIENCE DIRECT
TITLE-ABS-KEY: (*cobots OR (collaborative robotics) OR (human-robot collaboration) OR (human-robot cooperation)) AND control*
SUBJECT AREAS: *engineering, computer science,* and *decision science*
YEARS: From 2015 onwards
N PAPERS FOUND: 265
30 papers

IEEE journal papers
TITLE-ABS-KEY: (*cobots OR (collaborative robotics) OR (human-robot collaboration) OR (human-robot cooperation)) AND control*
YEARS: From 2015 onwards
N PAPERS FOUND: 380 (64 T-ASE/T-RO)
64 papers (21 T-ASE/ T-RO)

SCOPUS
TITLE-ABS-KEY: (*cobots OR (collaborative robotics) OR (human-robot collaboration) OR (human-robot cooperation)) AND control*
YEARS: From 2015 onwards
N PAPERS FOUND: 1865
8 papers

120 papers



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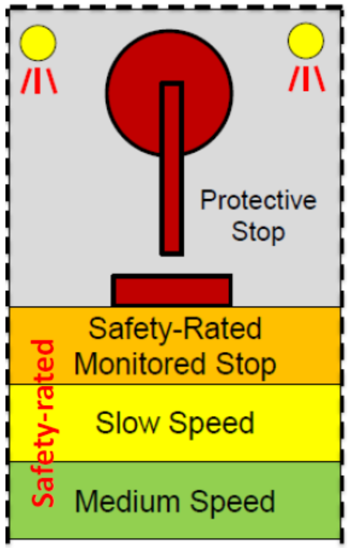
[5]: Proia, Silvia, et al. "Control Techniques for Safe, Ergonomic, and Efficient Human-Robot Collaboration in the Digital Industry: A Survey." IEEE Transactions on Automation Science and Engineering (2021).

SURVEY ON HRC CONTROL TECHNIQUES



DEFINITION OF SAFETY IN COBOTICS

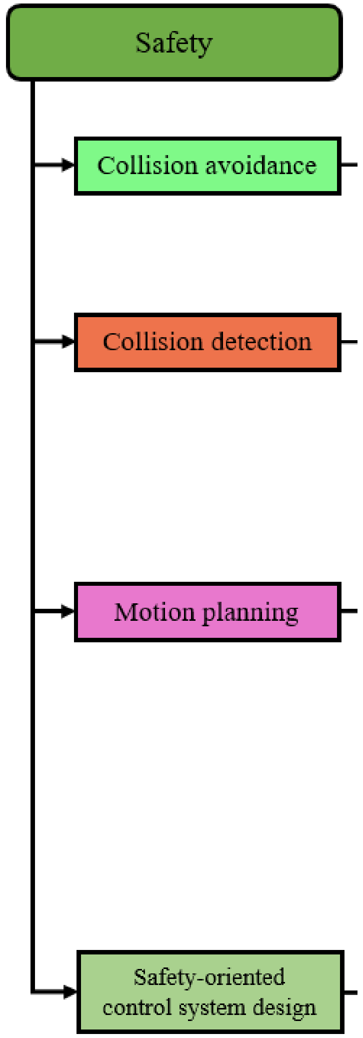
Safety is a fundamental requirement that allows operators to work side-by-side with “fenceless” robots in compliance with **ISO/TS 15066** standards, i.e., limitation of maximum permissible forces or torques, speed reduction, and respect for a minimum protective separation distance

NUMBER OF PAPERS FROM THE SAFETY PERSPECTIVE

59 % (71 out of 120)

CLASSIFICATION OF THE PAPERS ACCORDING TO 4 CONTROL PROBLEMS

- Collision avoidance
- Collision detection
- Motion planning
- Safety-oriented control system design



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SURVEY ON HRC CONTROL TECHNIQUES

COLLISION AVOIDANCE

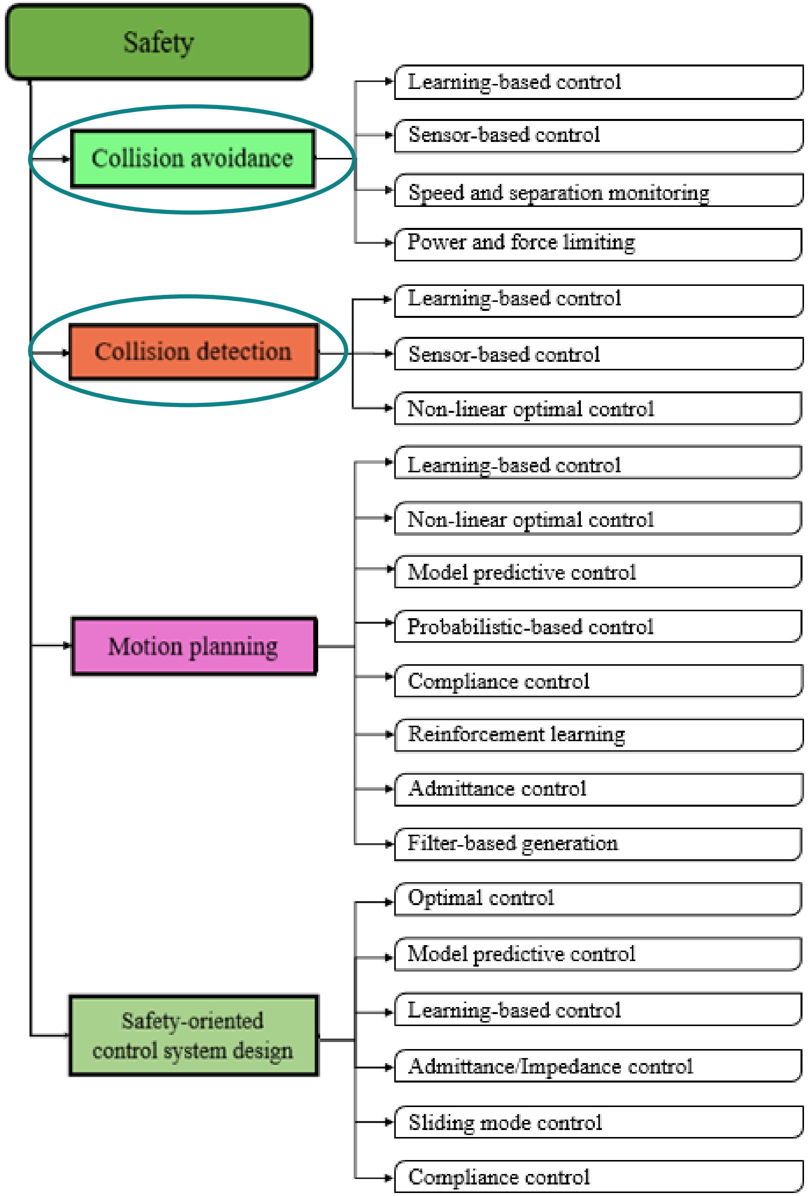
Main observations

- The estimation of human impedance and motion intention is mostly achieved by **learning-based techniques**
- **Multi-sensor control systems** detect the human presence and evaluate in real-time the HR distance
- **Speed and separation monitoring** and **Power and force limiting** are compatible with the requirements of ISO/TS 15066

COLLISION DETECTION

Main observations

- The majority of the works aims at designing an **observer** to estimate the internal state needed to detect collisions
- Only one contribution presents a **non-linear optimization problem** (genetic algorithm)



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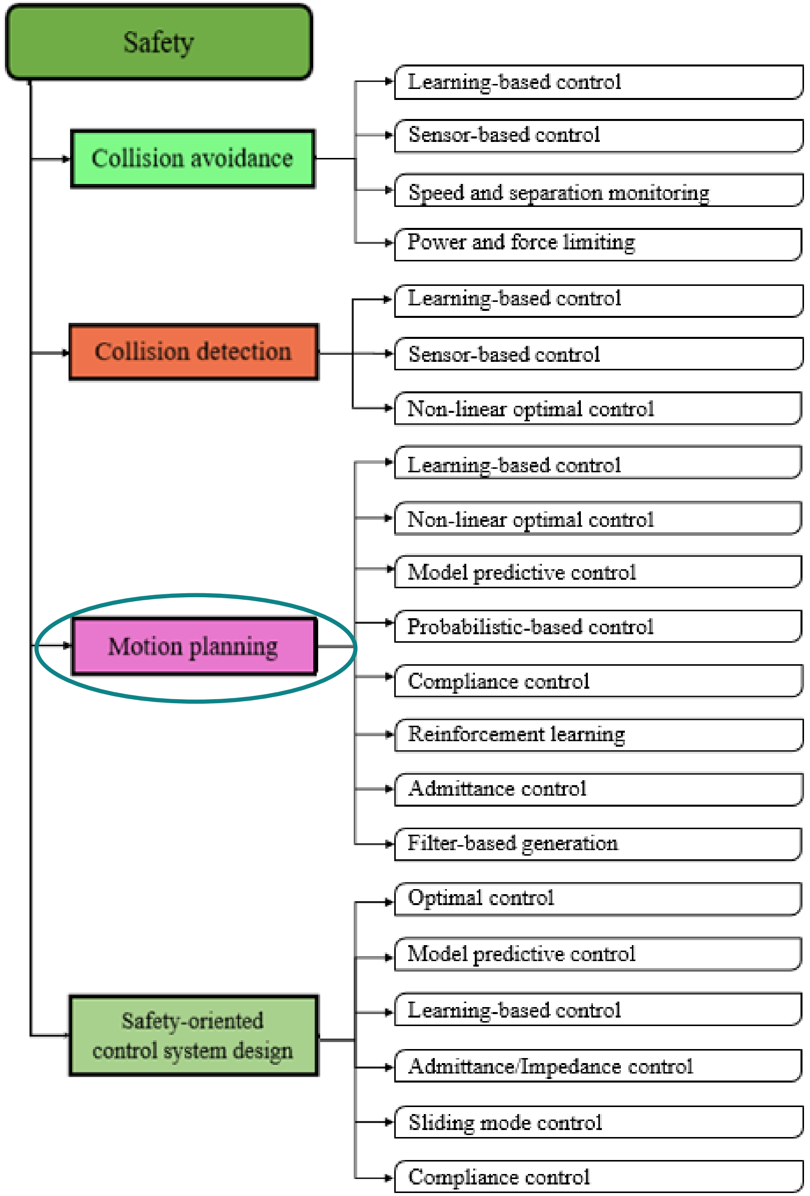
SURVEY ON HRC CONTROL TECHNIQUES

MOTION PLANNING

Main observations

- Trajectory planning allows to reduce the risk of possible HR contacts, leveraging on the operator's motion prediction
- Most of the works formulate the trajectory planning as an **optimization problem**
- Some of the optimization-based control techniques implemented are:
  - **Convolutional neural networks**
  - **Fuzzy control logic**
  - **Non-linear programming**
  - **Stochastic trajectory optimizer**
  - **Dynamic movement primitives**



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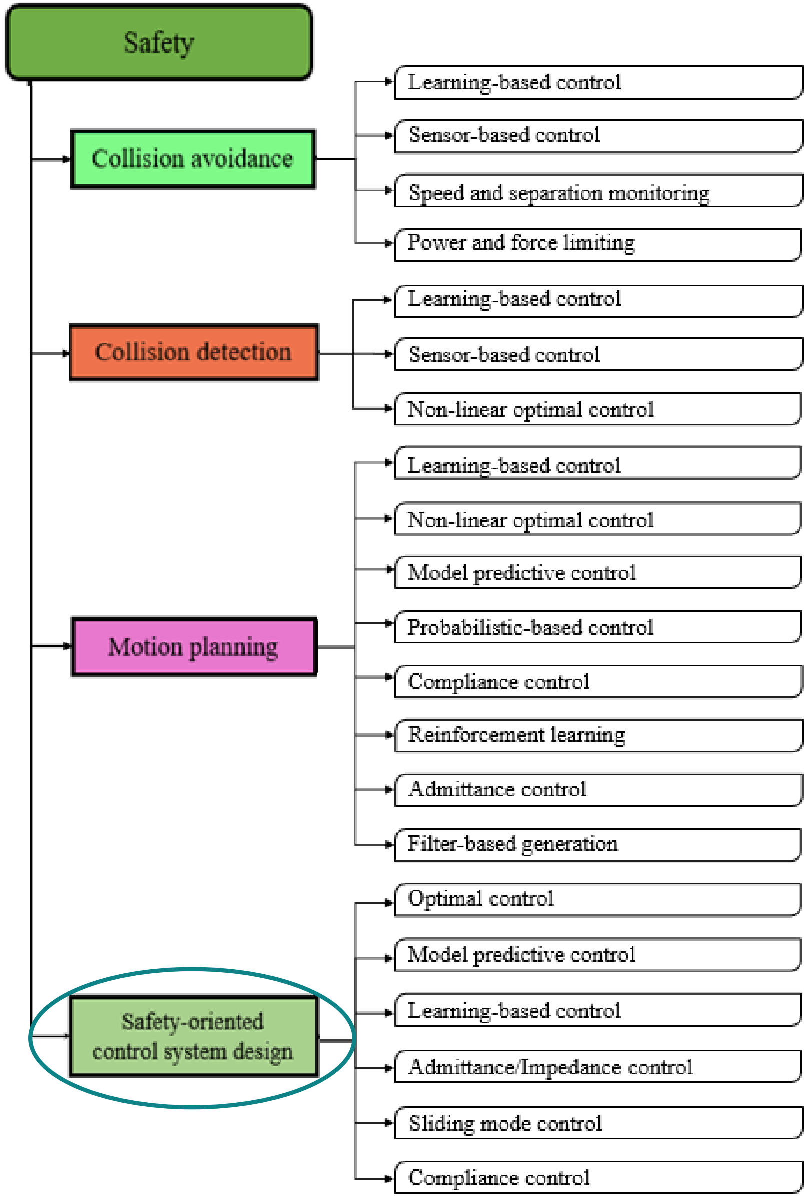
SURVEY ON HRC CONTROL TECHNIQUES

SAFETY-ORIENTED CONTROL SYSTEM DESIGN

Main observations

- All the works aim at designing advanced controllers for a safe HRC
- Some of the techniques implemented are:
  - **Linear quadratic regulator**
  - **Model predictive control**
  - **Recurrent neural networks**
  - **PID-based control**
  - **Energy-tanks** (for passivity)



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SURVEY ON HRC CONTROL TECHNIQUES

DEFINITION OF ERGONOMICS IN COBOTICS

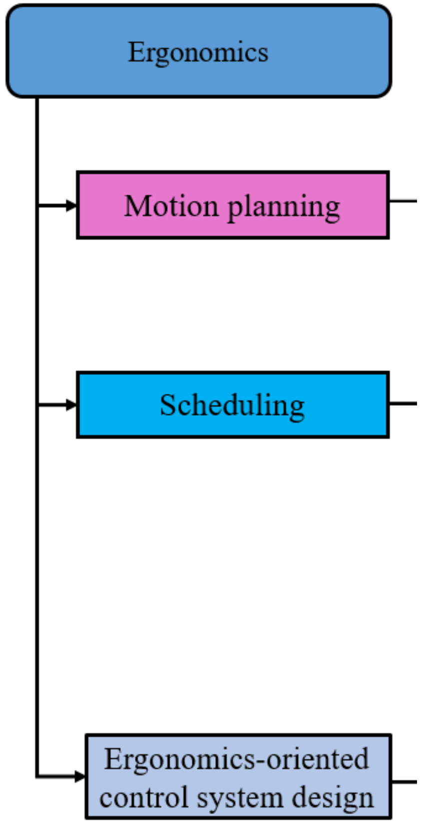
- **Physical ergonomics** is considered as the prevention of injuries associated with repetitive and dangerous tasks, and design and evaluation of workplaces
- **Cognitive ergonomics** is associated with brain functions in the context of accident investigation or error analysis, mental workload, decision making, usability, and training

NUMBER OF PAPERS FROM THE ERGONOMICS PERSPECTIVE

18 % (21 out of 120)

CLASSIFICATION OF THE PAPERS ACCORDING TO 3 CONTROL PROBLEMS

- Motion planning
- Scheduling
- Ergonomics-oriented control system design



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MOTION PLANNING

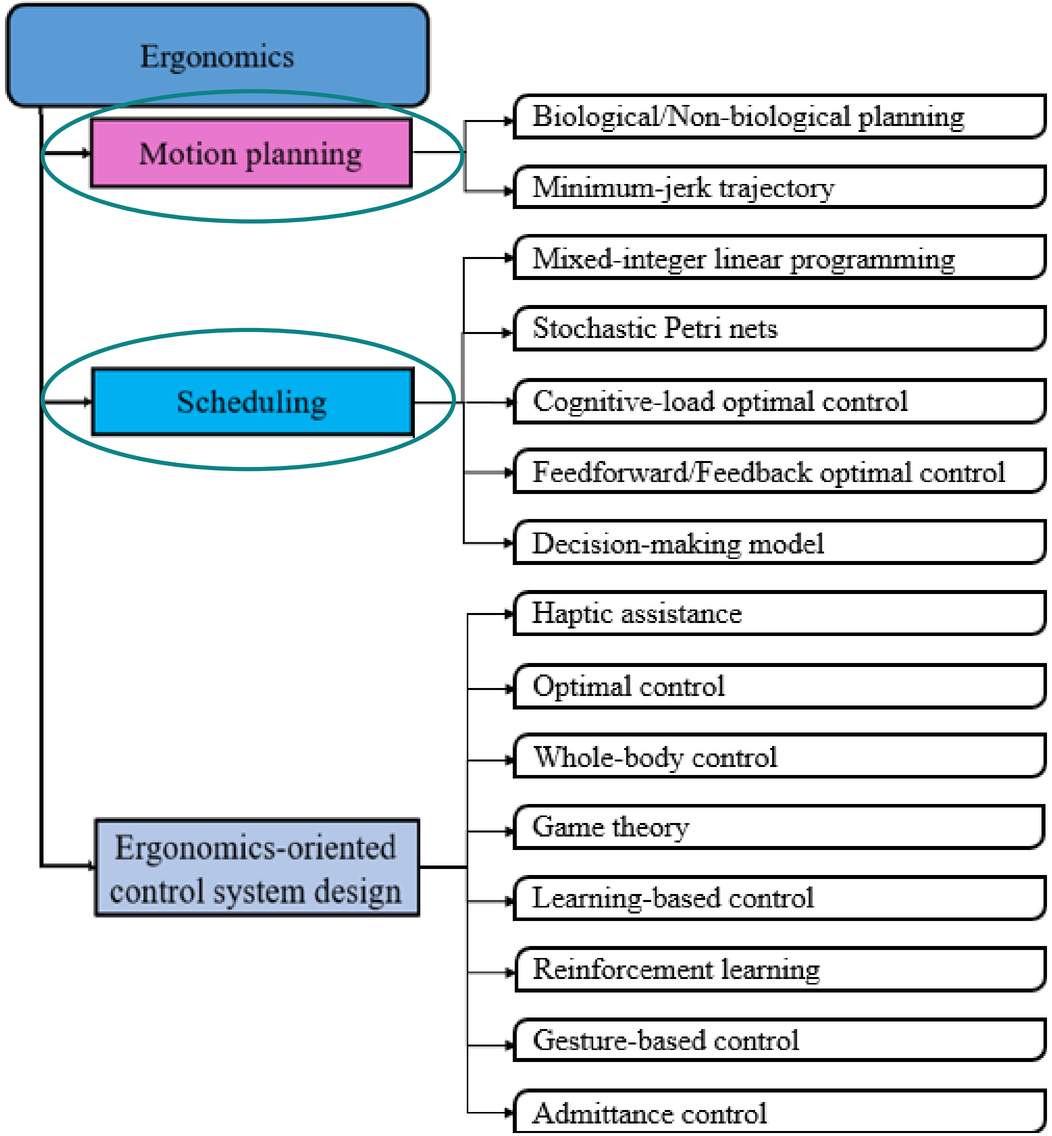
Main observation

- Only 2 out of 21 articles belong to this category

SCHEDULING

Main observation

- An optimal HR allocation of tasks alleviates the risk for musculoskeletal disorders resulting from repetitive movements and excessive fatigue of the operator



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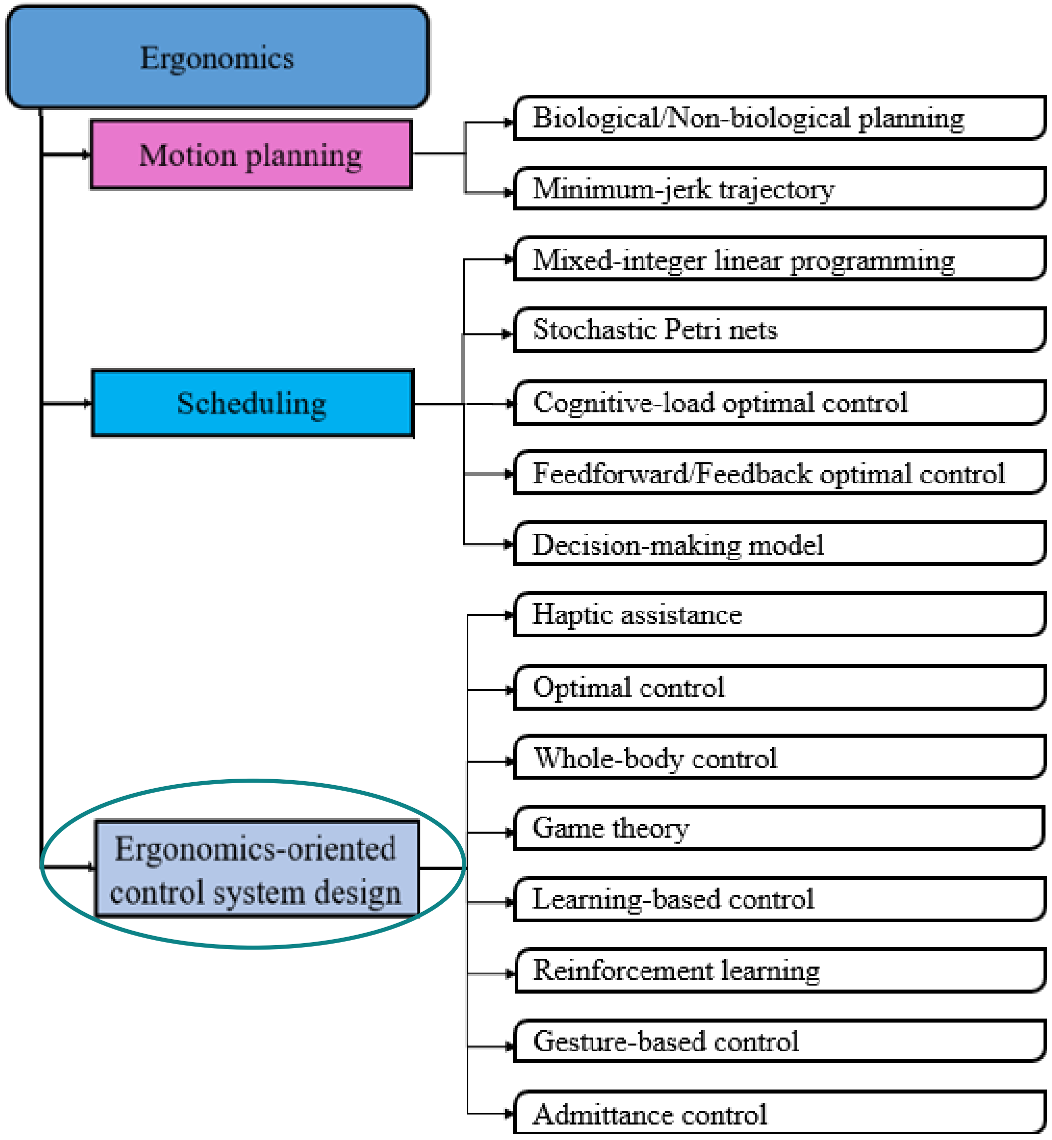
SURVEY ON HRC CONTROL TECHNIQUES

ERGONOMICS-ORIENTED CONTROL SYSTEM DESIGN

Main observations

- In the majority of works the goal is to minimize the human physical and cognitive discomfort in HRC by designing optimal control strategies
- The learning-based techniques used are:
  - **Reinforcement learning**
  - **Neural networks**



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DEFINITION OF EFFICIENCY IN COBOTICS

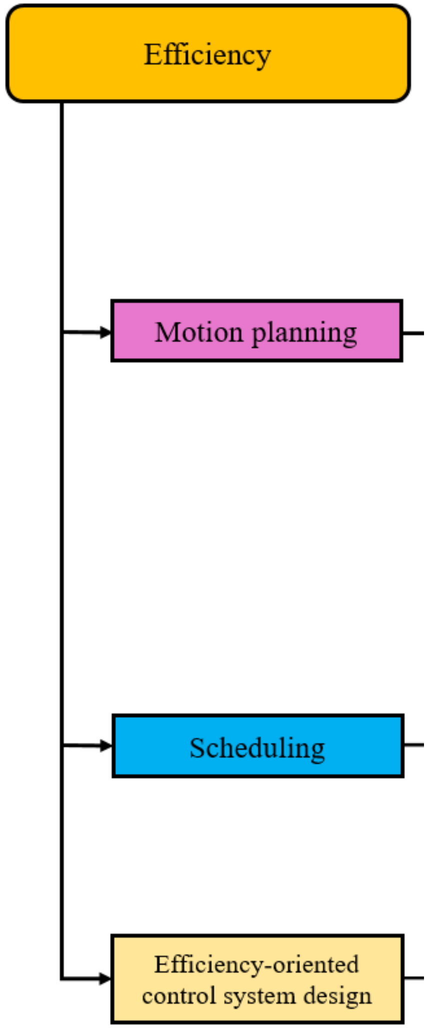
Efficiency is intended as the improvement of the entire industrial process or merely as the simplification of the operator’s actions to complete a task by scheduling activities or planning the actions performed by the worker and the robot in the optimal way

NUMBER OF PAPERS FROM THE EFFICIENCY PERSPECTIVE

23 % (28 out of 120)

CLASSIFICATION OF THE PAPERS ACCORDING TO 3 CONTROL PROBLEMS

- Motion planning
- Scheduling
- Efficiency-oriented control system design



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SURVEY ON HRC CONTROL TECHNIQUES

MOTION PLANNING

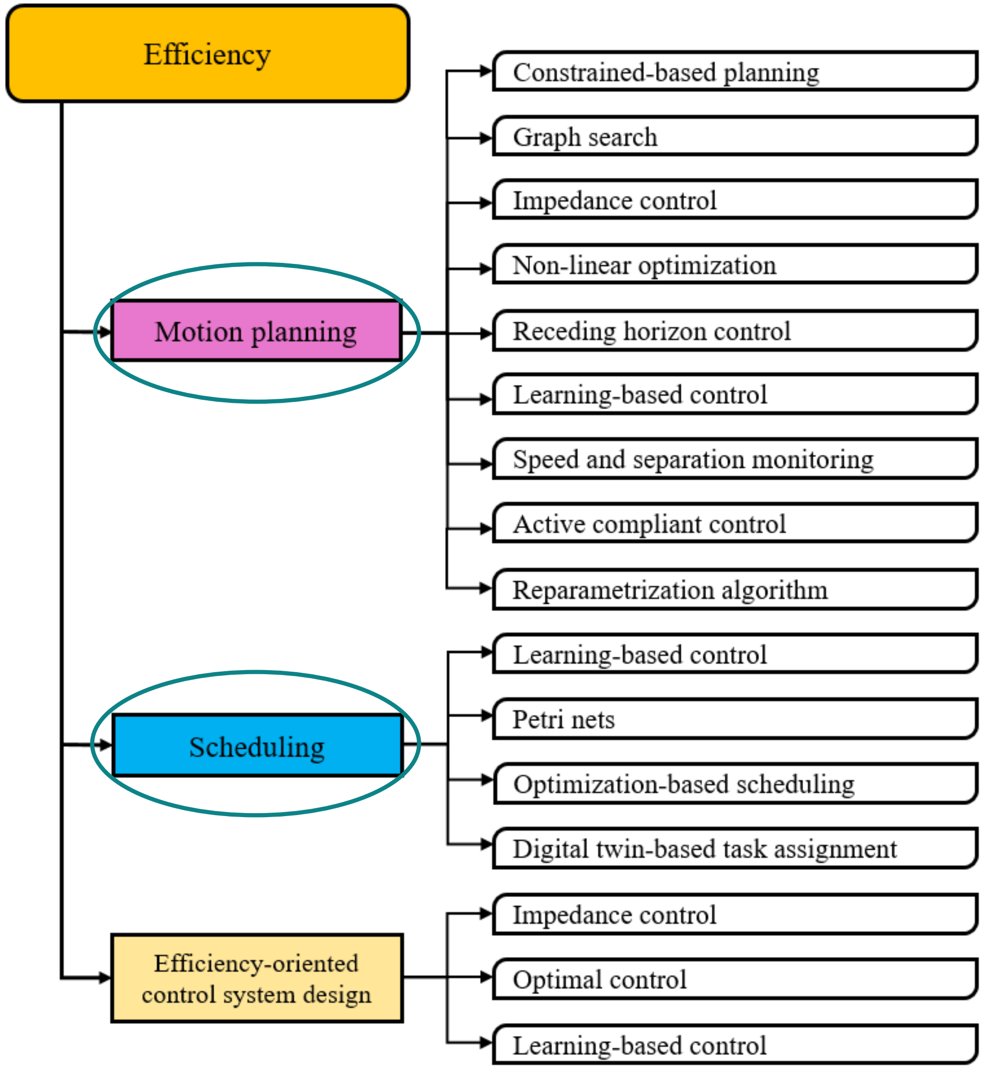
Main observation

- The robot trajectories' optimization aims at minimizing the time needed to complete an industrial task and/or at improving the quality and comfort of collaborative tasks

SCHEDULING

Main observation

- Some of the emerging control techniques used are:
  - **Reinforcement learning**
  - **Convolutional neural networks**
  - **Multi-criteria task assignment**
  - **Discrete Bees algorithm based on Pareto**



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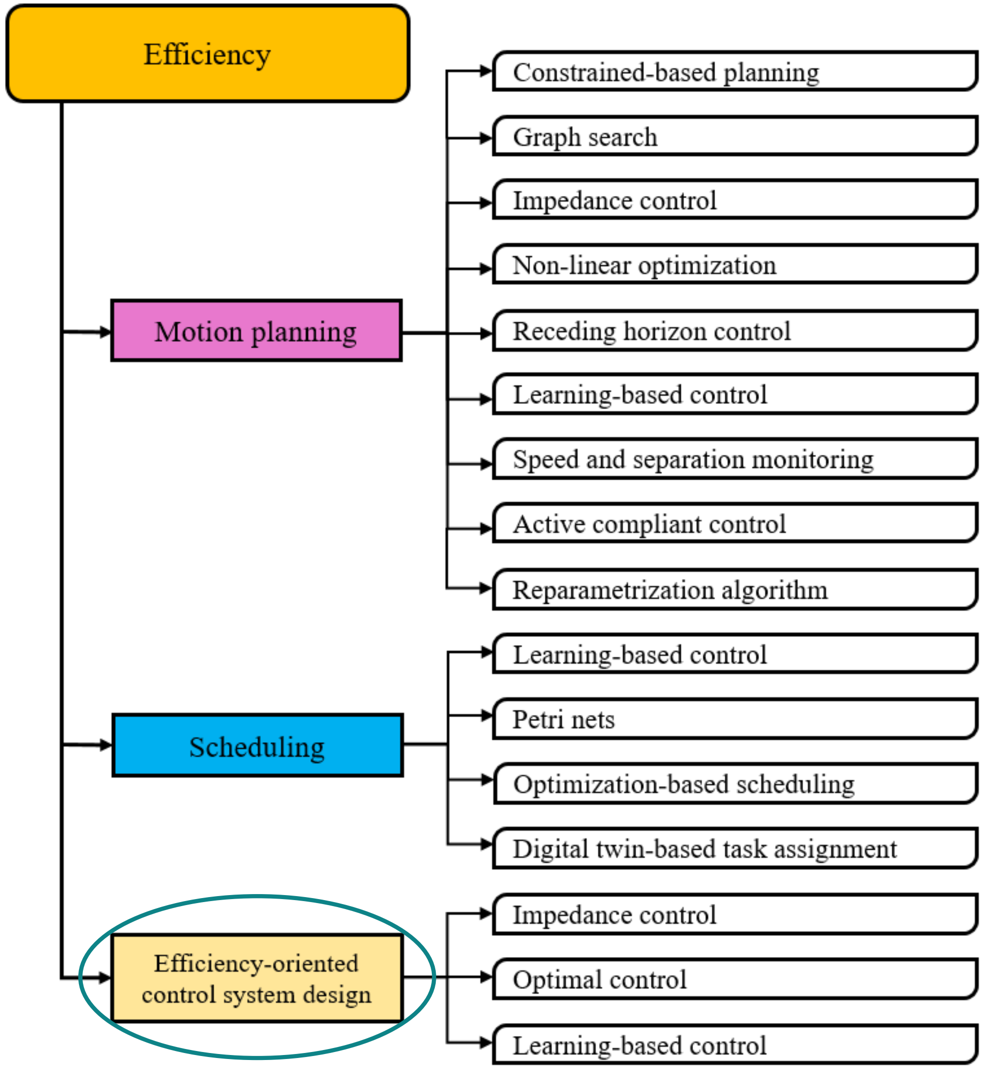
SURVEY ON HRC CONTROL TECHNIQUES

EFFICIENCY-ORIENTED CONTROL SYSTEM DESIGN

Main observations

- All the frameworks are designed to augment the performance and efficiency of a cooperative task and, thus, productivity and profitability of the digital factory
- Some of the control techniques used are:
  - **Pareto optimization**
  - **Linear quadratic regulator**
  - **Barrier Lyapunov function-based impedance control**
  - **Bayesian optimization**
  - **Learning from demonstration**
  - **Reinforcement learning**



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SURVEY ON HRC CONTROL TECHNIQUES

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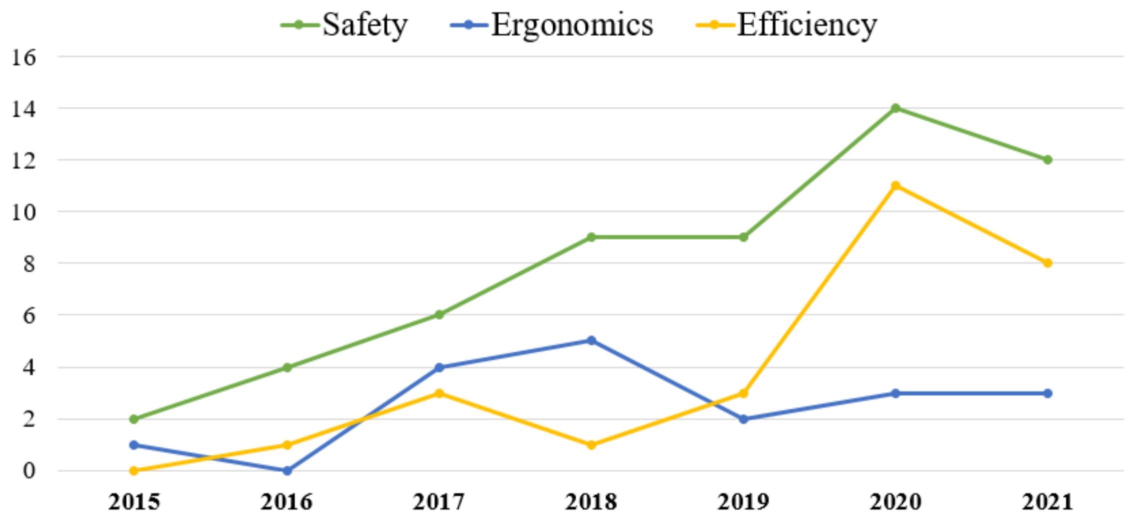
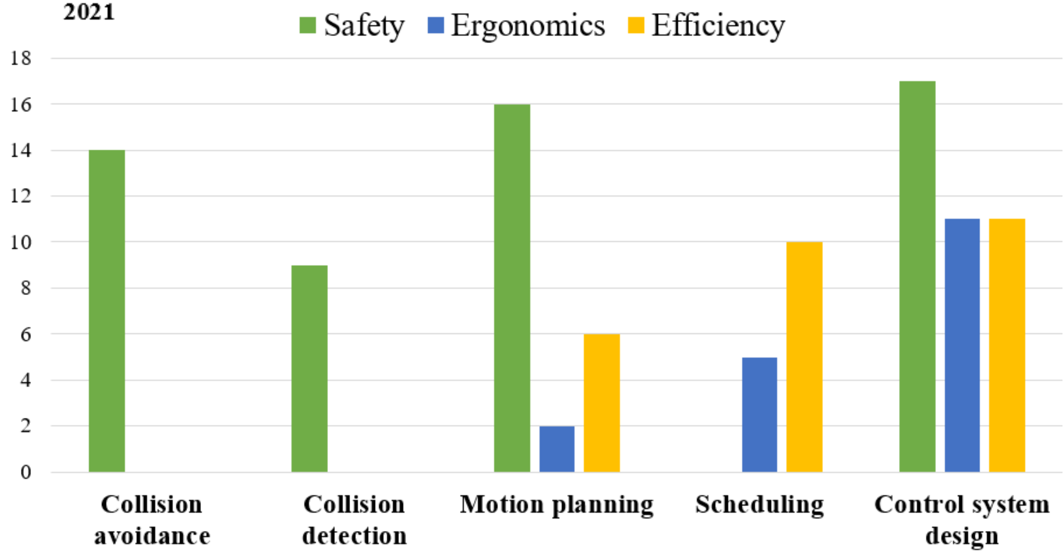
CURRENT RESEARCH TRENDS IN HRC CONTROL SYSTEMS



Annual distribution of the analyzed papers for each HRC target in the selected time span

Number of papers related to the analyzed control problems for each HRC target



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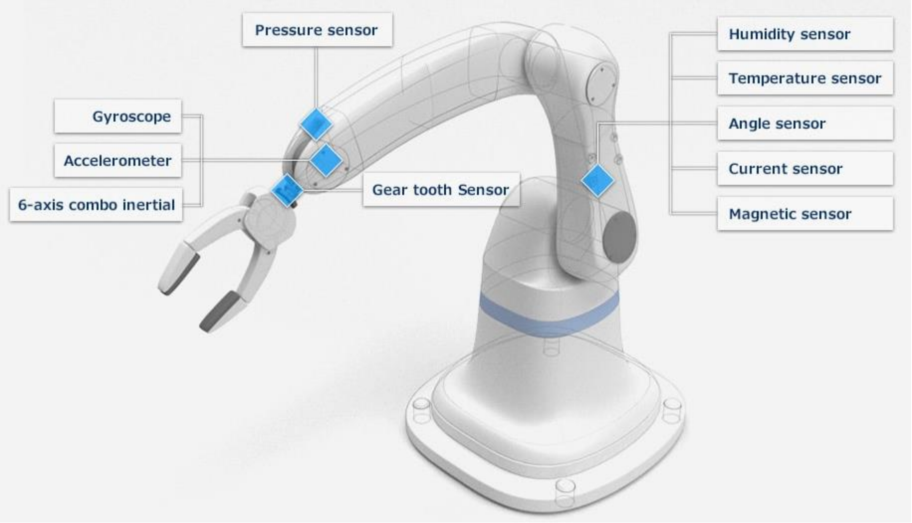
SURVEY ON HRC CONTROL TECHNIQUES

EMERGING CONTROL ISSUES AND CHALLENGES

Sensor-based methodologies

- These techniques are employed in a large number of HR collaborative tasks and can be of 4 types:
  - **audio-based**
  - **touch-based**
  - **vision-based**
  - **distance-based**
- In general, they are combined with **virtual and augmented reality**

- They are involved in fully integrated robotic systems to collect and learn the huge amount of data that are used to predict the human movements during the interaction with robots
- The cons are:
  - Visible degrees of hysteresis
  - Non-stationarity
  - Other mechanical nonlinearities



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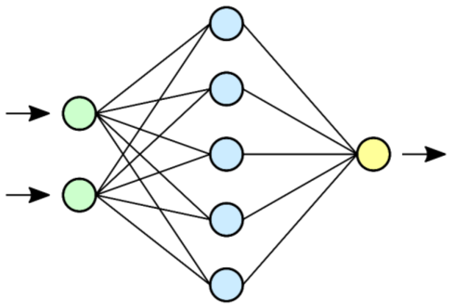
EMERGING CONTROL ISSUES AND CHALLENGES
Learning-based methodologies

- They aim at introducing an analysis of the human behavior to avoid unsafe situations or facilitate the HRC by predicting in real time the human behavior and thus control accordingly the robot; the most employed methodologies are:
  - **Recurrent Neural Networks**
  - **Feedforward Neural Networks with radial basis function**
  - **Convolutional Neural Networks**



- The pros are:
  - High generalization performance
  - Capability to approximate an arbitrary function with adequate number of neurons
  - Learning from demonstration
- The cons are:
  - Huge computation time
  - Limited generalizability or adaptability to unseen situations
- To overcome the issues, NNs are combined with **admittance/impedance** control, **stochastic** control techniques, and **optimization-based** methods or they are based on techniques like **Sliding mode control**, **Takagi-Sugeno fuzzy control**, and **Reinforcement learning**

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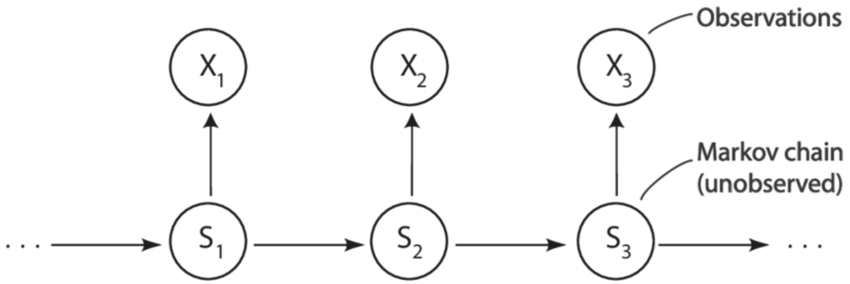
SURVEY ON HRC CONTROL TECHNIQUES

EMERGING CONTROL ISSUES AND CHALLENGES
Impedance/admittance control methodologies

- **Impedance** technique controls motion after the force's detection in dynamic interaction with stiff environments
- In some cases, impedance control integrates an **energy tank** as a tool for Passivity-Based Control in order to guarantee asymptotic stability in non-passive environment
- **Admittance** technique controls force after the measurement of motion or deviation from a set point in interaction with soft environments or operation in free space

EMERGING CONTROL ISSUES AND CHALLENGES
Stochastic methodologies

- The most employed techniques are:
  - **Bayesian robot programming**
  - **Hidden Markov model**
  - **Gaussian mixture model**



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EMERGING CONTROL ISSUES AND CHALLENGES

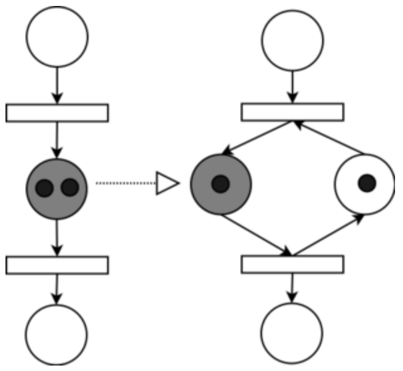
Optimization-based methodologies

- They are implemented to improve the calculator performance and develop high-speed algorithms or to respect the new ISO safety requirements
- They are often combined with:
  - **Learning-based techniques**
  - **Sensor-based techniques**
- In the future, they can be integrated with:
  - **Model Predictive Control**
  - **Human gesture prediction**

EMERGING CONTROL ISSUES AND CHALLENGES

Optimization-based methodologies for optimal tasks allocation

- The most employed techniques are:
  - **Integer linear programming**
  - **Mixed integer linear programming**
  - **Graph search**
  - **Timed/stochastic Petri nets**



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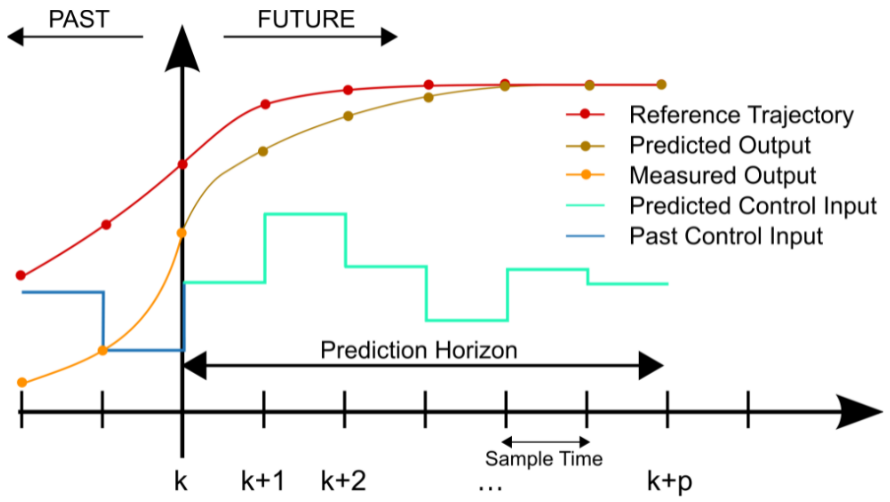
SURVEY ON HRC CONTROL TECHNIQUES

EMERGING CONTROL ISSUES AND CHALLENGES

Model Predictive Control

- The cons are:
  - Computational complexity
  - High number of control variables
  - Derivation of the complex robot's dynamic models
- To overcome these issues, it can be combined with:
  - **Admittance/impedance control**
  - **Stochastic techniques**



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TRENDS AND CHALLENGES

CURRENT TRENDS

- **None** of the reviewed articles is **simultaneously** focused on all the **three targets** (i.e., safety, ergonomics, and efficiency)
- 12% (**14** papers) of the selected works are written accordingly to **dual targets**: 8 papers are formulated from the safety/efficiency control perspective, 2 papers from safety/ergonomics control perspective, and 4 papers from ergonomics/efficiency control perspective
- The control techniques are usually applied to the **assembly** or **disassembly** processes

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TRENDS AND CHALLENGES

CHALLENGES

- HRC research will have to deal with the **three objectives** (i.e., safety, ergonomics, and efficiency) **at the same time**
- The indices **RULA** (rapid upper limb assessment) and **REBA** (rapid entire body assessment), can be integrated as assessment tools in the optimization processes to evaluate the exposure of individual workers to ergonomic risk factors
- The industrial HRC **application context** can be **expanded** [1-3]
- The control techniques can be experimented and tested even more in **real case studies** directly in the industrial setting

[1]: "Universal Robots website," https://www.universal-robots.com/, accessed: 2021-07-29
[2]: "Rethink Robotics website," https://www.universal-robots.com/, accessed: 2021-07-29
[3]: "Omron website," https://www.universal-robots.com/, accessed: 2021-07-29

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TRAJECTORY PLANNING

GOAL [6-7]

- The aim is to deal with the **three** pivotal **targets** (i.e., safety, ergonomics, and efficiency) in the manufacturing scenario in a **trajectory planning** optimization problem by ensuring the best compromise between traversal **time** of the trajectory for the **cobot** and **ergonomics** for the **human worker**

↓

MULTI-OBJECTIVE OPTIMIZATION APPROACH FOR THE TRAJECTORY PLANNING IN SAFE AND ERGONOMIC HRC

- Minimization of **RULA** ➡ Ergonomics
- Optimization of **time** ➡ Efficiency
- **ISO requirements** compliance ➡ Safety
- **Application**: pick and place, accurate assembly, material removal or any other precise application associated with the ”3D” (Dull, Dirty, Dangerous)

[6]: S. Proia, R. Carli, G. Cavone, M. Dotoli, "A Trajectory Planning Optimization Approach for a Safe and Ergonomic Human-Robot Collaboration.“ 2022 IEEE 18th International Conference on Automation Science and Engineering (CASE). IEEE, 2022 (submitted).
[7]: S. Proia, A. Camposeo, F. Ceglie, G. Cavone, R. Carli, M. Dotoli, "A Safe and Ergonomic Human-Drone Interaction in a Warehouse Environment.“ 2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, 2022 (submitted).

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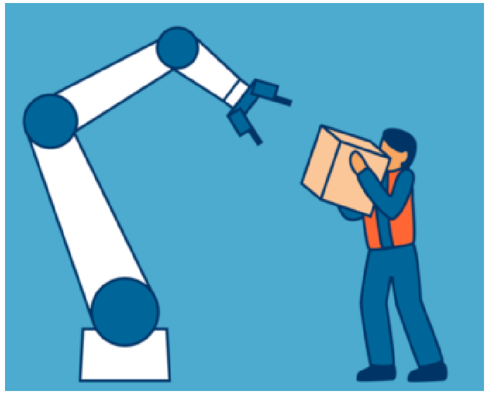
TRAJECTORY PLANNING

TRAJECTORY PLANNING LITERATURE REVIEW

- Multi-objective optimization of time and energy but **never of ergonomics**
- Application only on traditional industrial manipulators
  - Three categories based on the programming methodology:
    - **Direct transcription methods** [8-10]
    - **Indirect methods** [11]
    - **Dynamic programming methods** [12]



[8]: Verscheure, Diederik, et al. "Practical time-optimal trajectory planning for robots: a convex optimization approach." *IEEE Transactions on Automatic Control* (2008).

[9]: Betts, John T., and William P. Huffman. "Path-constrained trajectory optimization using sparse sequential quadratic programming." *Journal of Guidance, Control, and Dynamics* 16.1 (1993): 59-68.

[10]: Mora, Pedro Reynoso. *On the Time-optimal Trajectory Planning along Predetermined Geometric Paths and Optimal Control Synthesis for Trajectory Tracking of Robot Manipulators*. University of California, Berkeley, 2013.

[11]: Shin, Kang, and Neil McKay. "A dynamic programming approach to trajectory planning of robotic manipulators." *IEEE Transactions on Automatic Control* 31.6 (1986): 491-500.

[12]: Shin, Kang, and Neil McKay. "Minimum-time control of robotic manipulators with geometric path constraints." *IEEE Transactions on Automatic Control* 30.6 (1985): 531-541.

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TRAJECTORY PLANNING

EVALUATION OF ERGONOMICS

- **RULA** ➡ tool for assessing the exposure of workers to risk factors that can generate trauma in the upper limbs of the body

Score	Level of MSD Risk
1-2	negligible risk, no action required
3-4	low risk, change may be needed
5-6	medium risk, further investigation, change soon
6+	very high risk, implement change now

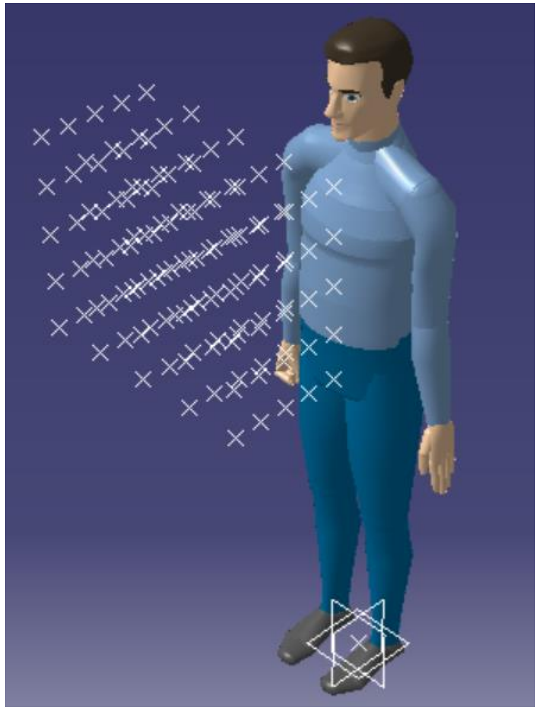
- Size of the volume created on the CAD software **CATIA**

$$X_{min} = 0.2 \text{ m} \qquad X_{max} = 0.5 \text{ m}$$

$$Y_{min} = -0.5 \text{ m} \qquad Y_{max} = 0.1 \text{ m}$$

$$Z_{min} = 1 \text{ m} \qquad Z_{max} = 1.5 \text{ m.}$$

- Design of a mannequin that simulates an operator
- Definition in the workspace of a generic volume that consists of equidistant points
- Evaluation of the RULA index for each point
- Optional: volume subdivision into regions with constant RULA
- Optional: Choice of region with minimum RULA



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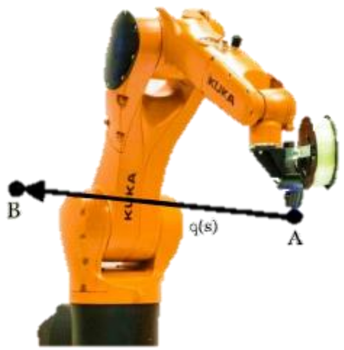
TRAJECTORY PLANNING

TIME-OPTIMAL TRAJECTORY PLANNING ALONG A PREDEFINED PATH

Definition of the input data to the problem
- Definition of the starting and end point of the path
- Definition of the initial and final orientation of the end effector
- Path generation in the Cartesian space

Design of the manipulator
- Definition of the Denavit-Hartenberg parameters and kinematic/dynamic indicators
- Inverse kinematic to find position, velocity and acceleration of all joints in the joint space
- Design of the dynamic model and computation of the Inertia matrix, Coriolis matrix, and Gravity vector

Resolution of the optimal control problem (non-linear, non-convex)
- Definition of the objective function and of the kinematic and dynamic constraints
- Problem reformulation in linear, convex, and SOCP
- Discretization and transformation into an optimization problem
- Problem resolution with the direct transcription method through a solver chosen ad hoc
- Acquisition of optimized variables



Summary of the performed steps

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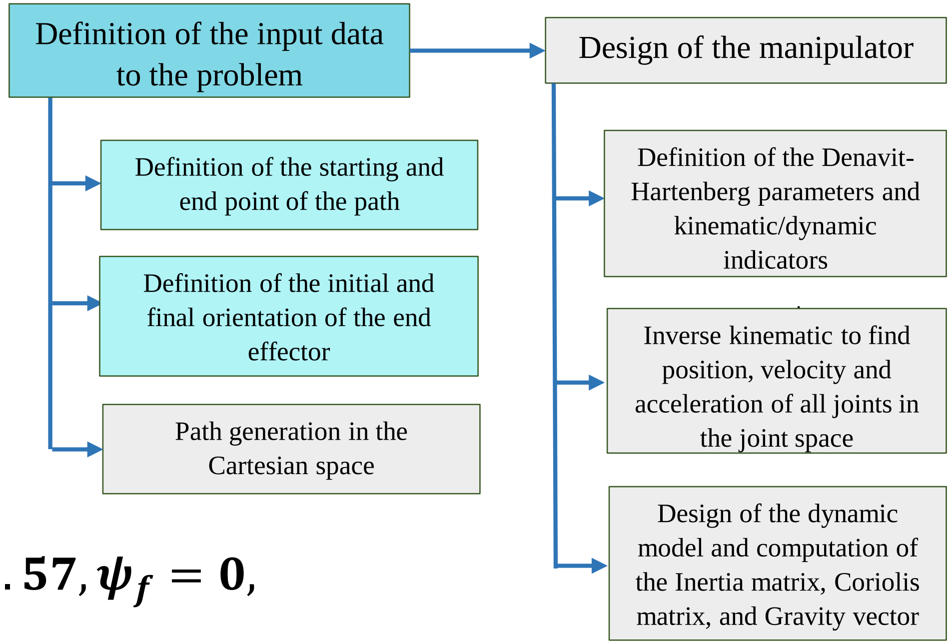
TRAJECTORY PLANNING

STARTING POINT OF THE PATH (fixed)

$\mathbf{P_i} = [\mathbf{Px}_i\ \mathbf{Py}_i\ \mathbf{Pz}_i]$ where $\mathbf{Px_i} = \mathbf{0.1},\ \mathbf{Py_i} = -\mathbf{0.3},\ \mathbf{Pz_i} = \mathbf{0.5}$

$\mathbf{\Phi_i} = [\boldsymbol{\phi}_\mathbf{i}\ \boldsymbol{\theta}_\mathbf{i}\ \boldsymbol{\psi}_i]$ where $\boldsymbol{\phi}_i = -\mathbf{1.2},\ \boldsymbol{\theta}_i = \mathbf{0.6},\ \boldsymbol{\psi}_i = \mathbf{2}$



END POINT (variable)

$\mathbf{P}_f = [\mathbf{Px}_f\ \mathbf{Py}_f\ \mathbf{Pz}_f]$ ➡ each point that constitutes the work volume designed in the systematic procedure for the evaluation of ergonomics

$\mathbf{\Phi_f} = [\boldsymbol{\phi}_\mathbf{f}\ \boldsymbol{\theta}_\mathbf{f}\ \boldsymbol{\psi}_f]$ where $(\boldsymbol{\phi}_f = -\mathbf{1.57}, \boldsymbol{\theta}_f = \mathbf{1.57}, \boldsymbol{\psi}_f = \mathbf{0},$

$\forall\ \mathbf{P_f} \in \{(\mathbf{Px_f}, \mathbf{Py_f}, \mathbf{Pz_f}) \mid \mathbf{0.2} \le \boldsymbol{P_x} < \mathbf{0.5}, -\mathbf{0.5} \le \boldsymbol{P_y} \le \mathbf{0.1}, \mathbf{1} \le \boldsymbol{P_z} < \mathbf{1.5}\}) \cup$

$(\boldsymbol{\phi}_f = -\mathbf{1.05}, \boldsymbol{\theta}_f = \mathbf{1.57}, \boldsymbol{\psi}_f = \mathbf{0}, \forall\ \mathbf{P_f} \in \{(\mathbf{Px_f}, \mathbf{Py_f}, \mathbf{Pz_f}) \mid \boldsymbol{P_x} = \mathbf{0.5}, \boldsymbol{P_z} = \mathbf{1.5}\})$

Angles in radians; Coordinates in meters

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INTRODUCTION

SURVEY

TRENDS AND CHALLENGES

TRAJECTORY PLANNING

CONCLUSIONS

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TRAJECTORY PLANNING

PATH IN CARTESIAN SPACE

$$\boldsymbol{p}(s) = \boldsymbol{p}_i + \frac{s(t)}{\left\|\boldsymbol{p}_f - \boldsymbol{p}_i\right\|}(\boldsymbol{p}_f - \boldsymbol{p}_i)$$

$$\boldsymbol{\Phi}(s) = \boldsymbol{\Phi}_i + \frac{s(t)}{\left\|\boldsymbol{\Phi}_f - \boldsymbol{\Phi}_i\right\|}(\boldsymbol{\Phi}_f - \boldsymbol{\Phi}_i)$$

INVERSE KINEMATICS

$$\boldsymbol{q}(s) \in \boldsymbol{R}^n$$

- Definition of the input data to the problem
  - Definition of the starting and end point of the path
  - Definition of the initial and final orientation of the end effector
  - Path generation in the Cartesian space
- Design of the manipulator
  - Definition of the Denavit-Hartenberg parameters and kinematic/dynamic indicators
  - Inverse kinematic to find position, velocity and acceleration of all joints in the joint space
  - Design of the dynamic model and computation of the Inertia matrix, Coriolis matrix, and Gravity vector

- The path coordinate s is a monotonically increasing functional $s(t) \in [0,1],\ i.e., \dot{s} > 0$
- The trajectory starts at $t = 0$ and ends at $t = T \rightarrow s(0) = 0 \leq s(t) \leq 1 = s(T)$

Dynamic equation of motion of an n-DOF robotic manipulator

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{F}_v\dot{\boldsymbol{q}} + \boldsymbol{F}_s\boldsymbol{sgn}(\dot{\boldsymbol{q}}) + \boldsymbol{g}(\boldsymbol{q}) = \boldsymbol{\tau}$$

- $\boldsymbol{\tau} \in \boldsymbol{R}^n$: Joint torques
- $\boldsymbol{M}(\boldsymbol{q}) \in \boldsymbol{R}^{nxn}$: Inertia matrix
- $\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}}) \in \boldsymbol{R}^{nxn}$: Coriolis matrix
- $\boldsymbol{F}_v, \boldsymbol{F}_s \in \boldsymbol{R}^{nxn}$: coefficients of viscous and Coulomb friction
- $\boldsymbol{g}(\boldsymbol{q}) \in \boldsymbol{R}^n$: Gravity vector

TRAJECTORY PLANNING

$$\dot{\boldsymbol{q}} = \boldsymbol{q}'(s)\dot{s}$$
$$\ddot{\boldsymbol{q}} = \boldsymbol{q}''(s)\dot{s}^2 + \boldsymbol{q}'(s)\ddot{s}$$

- *q'(s)* and *q''(s)*: first and second partial derivatives of the geometric path $q(s)$ with respect to the parameter *s*
- $\dot{s}$ and $\ddot{s}$: pseudo-speed and pseudo-acceleration along the path

Resolution of the optimal control problem (non-linear, non-convex)

- Definition of the objective function and of the kinematic and dynamic constraints
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- Acquisition of optimized variables

$$\underset{a(s),b(s),c(s),\boldsymbol{\tau}(s)}{\text{minimize}} \quad \int_{0_+}^{1_-} \frac{1}{c(s)} ds$$

subject to

$$b(0) = \dot{s}_0^2, b(1) = \dot{s}_T^2,$$
$$c(0) = \dot{s}_0, c(1) = \dot{s}_T,$$
$$\boldsymbol{\tau}(s) = \boldsymbol{a}_1(s)a(s) + \boldsymbol{a}_2(s)b(s) + \boldsymbol{a}_3(s),$$
$$\underline{\boldsymbol{\tau}} \le \boldsymbol{\tau}(s) \le \overline{\boldsymbol{\tau}},$$
$$\forall s \in [0,1],$$
$$b'(s) = 2a(s), c(s) = \sqrt{b(s)},$$
$$\boldsymbol{q}'(s)^2 b(s) \le \overline{\dot{\boldsymbol{q}}}(s),$$
$$\underline{\ddot{\boldsymbol{q}}}(s) \le \boldsymbol{q}''(s)b(s) + \boldsymbol{q}'(s)a(s) \le \overline{\ddot{\boldsymbol{q}}}(s),$$
$$b(s), c(s) \ge 0,$$
$$\forall s \in [0_+, 1_-].$$

- Integration interval: $[0_+, 1_-]$
- $a(s) = \ddot{s}, b(s) = \dot{s}^2, c(s) = \dot{s}$
- $\dot{b}(s) = b'(s)\dot{s} = 2\dot{s}\ddot{s} \leftrightarrow b'(s) = 2a(s)$
- Torque limits constraints:
$$-\overline{\boldsymbol{\tau}}(s) \le \boldsymbol{\tau}(s) \le \overline{\boldsymbol{\tau}}(s)$$
- Velocity limits constraints:
$$\boldsymbol{q}'(s)^2 b(s) \le \overline{\dot{\boldsymbol{q}}}(s)$$
- Acceleration limits constraints:
$$-\overline{\ddot{\boldsymbol{q}}}(s) \le \boldsymbol{q}''(s)b(s) + \boldsymbol{q}'(s)a(s) \le \overline{\ddot{\boldsymbol{q}}}(s)$$

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TRAJECTORY PLANNING

$$
\begin{aligned}
\underset{a_k, b_k, c_k, d_k, \boldsymbol{\tau}_k}{\text{minimize}} \quad & \frac{1}{2}[(1-\alpha)\Delta s_1(d(0_+)+d_2)+ \\
& \sum_{k=2}^{N-2} \Delta s_k(d_k+d_{k+1})+ \\
& (1-\alpha)\Delta s_{N-1}(d_{N-1}+d(1_-))] \\
\text{subject to} \quad & \\
& b_1 = \dot{s}_0^2, b_N = \dot{s}_T^2, \\
& c_1 = \dot{s}_0, c_N = \dot{s}_T, \\
& \boldsymbol{\tau}_k = \boldsymbol{a}_1(s_k)a_k + \boldsymbol{a}_2(s_k)b_k + \boldsymbol{a}_3(s_k), \\
& \underline{\boldsymbol{\tau}} \le \boldsymbol{\tau}(s_k) \le \overline{\boldsymbol{\tau}}, \\
& \left\| \begin{bmatrix} 2c_k \\ b_k - 1 \end{bmatrix} \right\|_2 \le b_k + 1, \\
& \boldsymbol{q}'(s_k)^2 b(s_k) \le \overline{\dot{\boldsymbol{q}}}(s_k), \\
& \underline{\ddot{\boldsymbol{q}}}(s_k) \le \boldsymbol{q}''(s_k)b(s_k) + \boldsymbol{q}'(s_k)a(s_k) \le \overline{\ddot{\boldsymbol{q}}}(s_k), \\
& \text{for } k = 1, \dots, N, \\
& b_{j+1} - b_j = \Delta s_j(a_{j+1} + a_j \quad \text{for } j = 1, \dots, N-1, \\
& b_l > 0, \ c_l > 0, \\
& \left\| \begin{bmatrix} 2 \\ c_l - d_l \end{bmatrix} \right\|_2 \le c_l + d_l \quad \text{for } l = 2, \dots, N-1, \\
& \left\| \begin{bmatrix} 2 \\ c(0_+) - d(0_+) \end{bmatrix} \right\|_2 \le c(0_+) + d(0_+), \\
& \left\| \begin{bmatrix} 2 \\ c(1_-) - d(1_-) \end{bmatrix} \right\|_2 \le c(1_-) + d(1_-).
\end{aligned}
$$

- Resolution of the optimal control problem (non-linear, non-convex)
  - Definition of the objective function and of the kinematic and dynamic constraints
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- Transformation of all constraints into second-order cone constraints (SOCs)
- Discretization of the objective function
- Discretization of constraints
- $d(s) = \frac{1}{c(s)} = \frac{1}{\dot{s}}$

The software chosen for solving the optimization problem with the direct method is CVX

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TRAJECTORY PLANNING

OPTIMIZED SPEED AND ACCELERATION VARIABLES

$$\dot{\boldsymbol{q}} = \boldsymbol{q}'(s)\dot{s} = \boldsymbol{q}'(s)c(s)$$

$$\ddot{\boldsymbol{q}} = \boldsymbol{q}''(s)\dot{s}^2 + \boldsymbol{q}'(s)\ddot{s} = \boldsymbol{q}''(s)b(s) + \boldsymbol{q}'(s)a(s)$$

Resolution of the optimal control problem (non-linear, non-convex)

- Definition of the objective function and of the kinematic and dynamic constraints
- Problem reformulation in linear, convex, and SOCP
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TOTAL TRAVERSAL TIME

$$t(s_k) = t\,(s_{k-1}) + \frac{1}{2}\Delta s_{k-1}(d_{k-1} + d_k)$$

- Computed from the fixed starting point to each end point that constitutes the work volume of the human operator
- Chosen by making a trade-off with the ergonomic index RULA in the multi-objective optimization approach

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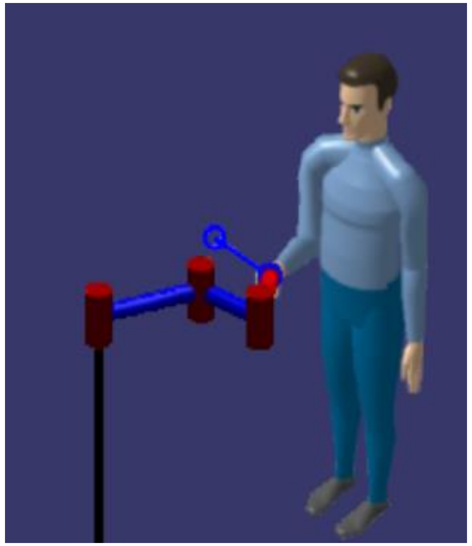
TRAJECTORY PLANNING



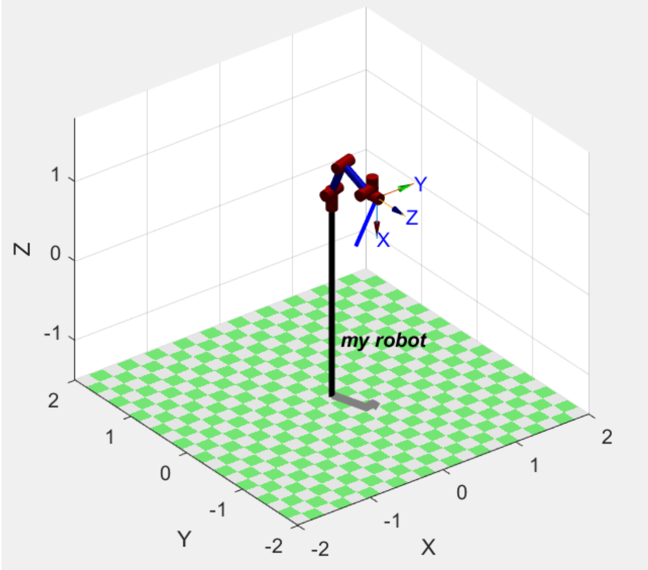
GENETIC ALGORITHM

$$\min_{x,P_f}[\alpha_1 f_1(x,P_f)+\alpha_2 f_2(P_f)] =$$

$$\min_{P_f}\left[\alpha_1 \min_{x} f_1(x,P_f)+\alpha_2 f_2(P_f)\right] = \min_{P_f}[\alpha_1 f_1{}'(P_f)+\alpha_2 f_2(P_f)]$$

where $f_1'(P_f) = \min_{x} f_1(x,P_f)$

- $P_f = [Px_f \ Py_f \ Pz_f]$
- $x = (a(s), b(s), c(s), \tau(s)^T)^T$
- f_2 = evaluation of the RULA index for each end point of the trajectory traveled by the end effector of the cobot
- $f_1{}'$ = time-optimal trajectory planning along the predefined path
- α_1, α_2 = weights of the multi-objective optimization problem



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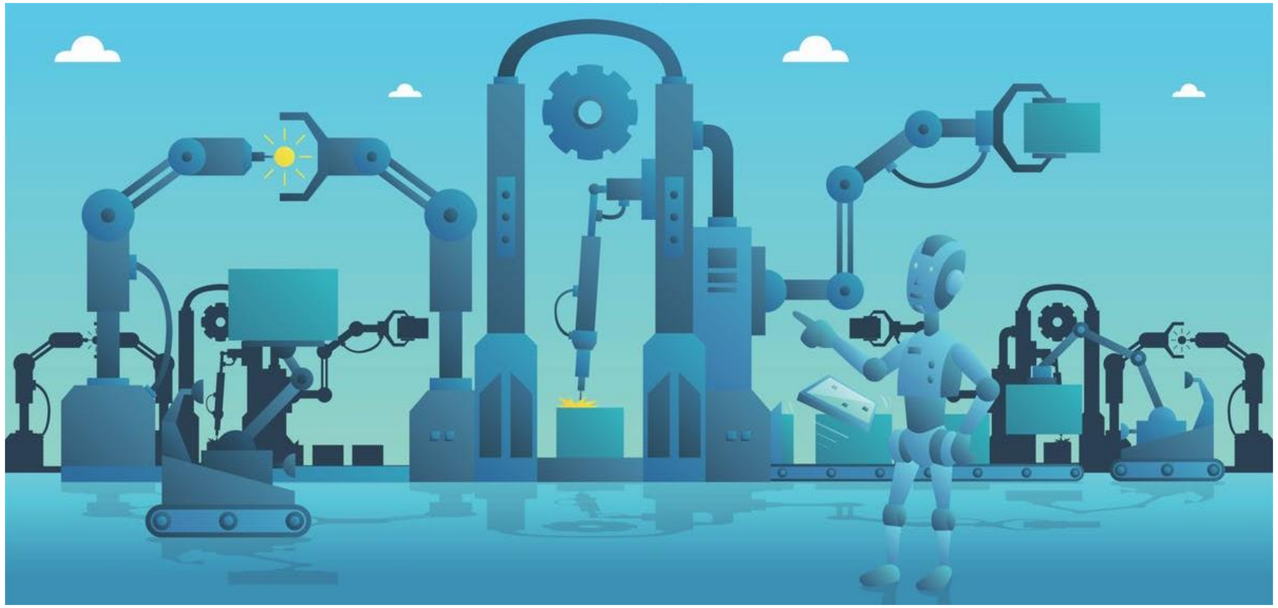
CONCLUSIONS

CONCLUSIONS

- The analysis of the state-of-the-art of cobotics is essential for researchers to identify **gaps** and **future developments** in this context of digital evolution
- The categorization of the main works related to a safe, ergonomic, and efficient HRC and the **identification** of the **existing control techniques** will be useful to improve the current methodologies and seek **alternative solutions**
- Simultaneous optimization of the **three targets** (i.e., safety, ergonomics, and efficiency) in trajectory planning problems



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CONCLUSIONS

FUTURE DEVELOPMENTS

- Extension of the current study to control techniques for **trajectory tracking** problems, **collision avoidance** and **collision detection** issues
- **Replanning** of the trajectory with the **operator moving** instead of standing still in space
- In-depth study of up to date optimization methods like **Dynamic Programming**, **Model Predictive Control**, and **Reinforcement Learning**
- Test of the mathematical assumptions and the defined control architectures in **simulation environments** and in **physical experiments** on real cobots

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Thanks for your attention!

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