Human-Robot Collaboration
in industry and beyond

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7 tech trends common to multiple industrial sectors and 3 more specific

A. De Luca – HRC – Saperi
Collaborative, Autonomous, Interactive ...

Source: Springer Handbook of Robotics
Robotics

intelligent connection of perception to action

CONTROL → ACTUATORS → SENSORS

visual data
motor commands
arm/hand control
haptic data
Robots and humans

science fiction and popular notions of robotics have long foreseen humans and robots existing side-by-side and collaborating to do work together

factory floors ...

... no humans!?
Crashes & collisions in industrial settings

unexpected effects of disturbances!

bad motion programming!!
Robot kills worker at Volkswagen plant in Germany

Contractor was setting up the stationary robot when it grabbed and crushed him against a metal plate at the plant in Baunatal

Associated Press in Berlin
Thursday 2 July 2015 02.48 BST

A robot has killed a contractor at one of Volkswagen’s production plants in Germany, the automaker has said.

The man died on Monday at the plant in Baunatal, about 100km (62 miles) north of Frankfurt, VW spokesman Heiko Hillwig said.

The 22-year-old was part of a team that was setting up the stationary robot when it grabbed and crushed him against a metal plate, Hillwig said.

He said initial conclusions indicate that human error was to blame, rather than a problem with the robot, which can be programmed to perform various tasks in the assembly process. He said it normally operates within a confined area at the plant, grabbing auto parts and manipulating them.

Another contractor was present when the incident occurred, but was not harmed, Hillwig said. He declined to give any more details about the case, citing an ongoing investigation.

German news agency DPA reported that prosecutors were considering whether to bring charges, and if so, against whom.
Laws of Robotics by Isaac Asimov in *I, Robot* (1950)

1. A robot may not injure a human being or, through inaction, allow a human being to come to harm
2. A robot must obey orders given to it by human beings, except where such orders would conflict with the First Law
3. A robot must protect its own existence as long as such protection does not conflict with the First or Second Law

More from Asimov (1920-1992) ...

- We cannot leave to AI decisions which may have safety, moral and legal consequences because we cannot ensure the outcome
- Yet we can have AI in robotics with proper technology
Traditional industrial perspective

- safeguarding/stopping the robot when a human is in the workspace
- monitoring workspace with sensors to slow down/stop robot motion
Innovative industrial perspective

- robot co-workers ...
Industrial revolutions

“comprehensive transformation of the whole sphere of industrial production through the merging of digital technology and internet with conventional industry”

(Angela Merkel - Organization for Economic Cooperation and Development, 2014)

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Industry 4.0

a list of **key enabling technologies** for the 4th industrial revolution

<table>
<thead>
<tr>
<th>Advanced Manufact. Solutions</th>
<th>Collaborative robots</th>
<th>networked and easily programmable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additive Manufacturing</td>
<td></td>
<td>• 3D additive printers with software for digital design</td>
</tr>
<tr>
<td>Augmented Reality</td>
<td></td>
<td>• Augmented reality to support production processes</td>
</tr>
<tr>
<td>Simulation</td>
<td></td>
<td>• Simulation tools of interconnected machines/cells for process optimization</td>
</tr>
<tr>
<td>Horizontal/Vertical Integration</td>
<td></td>
<td>• Integration of information along the value chain from suppliers to customers</td>
</tr>
<tr>
<td>Industrial Internet</td>
<td></td>
<td>• Bidirectional communication between production processes and products</td>
</tr>
<tr>
<td>Cloud</td>
<td></td>
<td>• Big data storage and exchange in open network systems</td>
</tr>
<tr>
<td>Cyber-security</td>
<td></td>
<td>• Security in operation of networks and open systems</td>
</tr>
<tr>
<td>Big Data and Analytics</td>
<td></td>
<td>• Big data analysis to optimize products and production processes</td>
</tr>
</tbody>
</table>
Collaborative robots

traditional robotics

replacing humans

human-friendly robotics

collaborating with humans

co-workers on factory floor

personal/service robots

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Industry 5.0 !!

Industry 5.0
Towards a sustainable, human-centric and resilient European industry

Digitalisation is ...
- Transforming European industry
- Accelerating production processes
- Changing the role of workers
This transformation is Industry 4.0

Industry 5.0 ...
- Human-centric
  - Promotes talents, diversity and empowerment
- Resilient
  - Is agile and resilient with flexible and adaptable technologies
- Sustainable
  - Leads action on sustainability and respects planetary boundaries
Human-Robot Interaction (HRI)

physical and cognitive interaction between a Sarcos robot and a human

intrinsic compliance and natural dynamic behavior of the robot are here more important than fast and accurate motion execution
cognitive vs physical HRI

cognitive interaction (cHRI) – Robot@CWE EU Project

physical interaction (pHRI) – handshaking at @PAL Robotics
Other physical HR interactions

- upper-limb and lower-limb exoskeletons for rehabilitation
- human augmentation
  - soft robotic system for improving worker ergonomics

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Human-robot collaboration

- **Mr. Helper** humanoid collaborates in carrying large and/or heavy loads [Tohoku University, 2000]

- **Kuka LWR4** with a Robotiq wrist force/torque sensor collaborates in an assembly task [2015]
Working with humans or for humans?

Application
- Multiple robot arms in collaboration with a human

[in 2017]

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State of the art on pHRI

- technical developments of components and systems for successful physical human–robot interaction over the last two decades
  - mechatronics (actuation/sensing), planning, and control
  - design of lightweight and compliant robots (and bioinspired soft robots!)
  - safe interaction control schemes
    ⇒ beyond high-payload/high-precision position-controlled industrial robots
- rise of a new generation of dependable robots capable of
  - sensing (or estimating) human motion and physical contacts
  - rendering natural and compliant behavior for the whole robot structure
  - planning legible motions that respect human preferences
  - generating interaction plans for collaboration and coaction with humans
- advances in the field of human safety in industrial robotics
- novel and unforeseen application domains are now open
Human-friendly robot design

Barrett arm

Mitsubishi PA10

DLR LWR III

KUKA LBR iiwa

DLR Rolling Justin

Rethink Robotics Baxter

NASA Robonaut

Boston Dynamics ATLAS
iF Design Award

DLR LBR III

Lightweight robot

7-dof arm designed by the Italian engineer Antonio Pascucci

first robot that carries a payload equal to its own weight (13.5 kg)!

$LBR = \text{LeichtBauRoboter} = \text{LWR} = \text{LightWeight Robot}$
Soft robots

- continuum soft manipulators
  - long, flexible, lightweight, slender arms
  - tendon/cable-driven, segmented, distributed/embedded actuation
  - energy efficient, (intentional) bio-inspired design
- useful in many special robotic applications
  - surgical, underwater, human interaction, cluttered environments, ...
Perception for interaction

- exteroceptive sensing
  - laser scanners, proximity sensors (magnetic, ultrasound, ...)
  - cameras (single, stereo, depth and RGB-D sensing, ...), Vicon system
Levels of pHRI

- Different possible levels of pHRI are defined also within the ISO 10218 safety standard for industrial robots (collaborative spaces)

ISO TS 15066:2016
Risk analysis and mitigation

Risk estimation process for each single hazard and combined risk mitigation measures exemplified.

<table>
<thead>
<tr>
<th>Most preferred</th>
<th>Least preferred</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inherently Safe Design Measures</td>
<td>Safeguarding &amp; Complementary Protective Measures</td>
</tr>
<tr>
<td>Elimination</td>
<td>Substitution</td>
</tr>
<tr>
<td>Process or layout design, redesign or modification</td>
<td>Less hazardous materials</td>
</tr>
</tbody>
</table>

Risk estimation process for each single hazard and combined risk mitigation measures exemplified.
Modification of power and force limits

an example of risk critical task ... mitigated by application re-design

1. Eliminate **pinch** and **crush** points
2. Reduce robot system **inertia** or **mass**
3. Reduce robot system **velocity**
   - 2. & 3. will reduce energy transfer in a collision
4. Modify robot posture such that **contact surface area** is increased
5. Avoid sensitive body areas (head & neck)

+ Safe control: collision detection & reaction
Human-friendly factory floor
From factories to our homes

industry
   automobile
   chemical
   electronic
   food

field
   aeronautics
   aerospace
   subsea
   rescue

service
   domestic
   edutainment
   rehabilitation
   medicine

level of autonomy

A. De Luca - Saperi
Levels of autonomy
surgical robotics

L0
No autonomy
Operator performs all tasks including monitoring, generating performance options, selecting the option to perform (decision-making), and executing the decision made.

L1
Robot assistance
Operator maintains continuous control of the system while the robot provides certain assistance.

L2
Task autonomy
Operator maintains discrete control of the system and the robot can perform certain operator-initiated tasks automatically.

L3
Conditional autonomy
Operator selects and approves a surgical plan and the robot performs the procedure automatically but with close surgical oversight by human.

L4
High autonomy
Robot is able to make decisions but under the supervision of a qualified operator.

L5
Full automation
No human needs to be in the loop, and the robot can perform an entire surgery.
Levels of autonomy
automotive

**L0**
No automation: the driver is in complete control of the vehicle at all times.

**L1**
Driver assistance: the vehicle can assist the driver or take control of either the vehicle’s speed, through cruise control, or its lane position, through lane guidance.

**L2**
Occasional self-driving: the vehicle can take control of both the vehicle’s speed and lane position in some situations, for example on limited-access freeways.

**L3**
Limited self-driving: the vehicle is in full control in some situations, monitors the road and traffic, and will inform the driver when he or she must take control.

**L4**
Full self-driving under certain conditions: the vehicle is in full control for the entire trip in these conditions, such as urban ride-sharing.

**L5**
Full self-driving under all conditions: the vehicle can operate without a human driver or occupants.

Source: SAE & NHTSA
A control architecture for safe pHRI

- planned and controlled robot behaviors in a 3-layer architecture

**Safety**
- lightweight mechanical design
- compliance at robot joints
- collision detection and reaction

**Coexistence**
- robot and human sharing the same workspace
- collision avoidance
- no need of physical contact

**Collaboration**
- contactless, e.g., gestures or voice commands
- with intentional contact and coordinated exchange of forces

A. De Luca, F. Flacco: *IEEE BioRob Conference, 2012*
Robotic crash tests

- Industrial robots-dummy without control
- KUKA LWR-dummy with collision detection/reaction
Collision detection and reaction

- first impact @60-90°/sec: robot detects, reacts, and floats
Human-robot coexistence

robot resumes its cyclic Cartesian task as soon as possible ...
From coexistence to collaboration

coexistence through collision avoidance

physical collaboration through contact identification (here, end-effector only)
On-line estimation of contact forces

Estimation of Contact Forces using a Virtual Force Sensor

Emanuele Magrini, Fabrizio Flacco, Alessandro De Luca

Dipartimento di Ingegneria Informatica, Automatica e Gestionale, Sapienza Università di Roma

February 2014
Contact force regulation with a “virtual” force sensor

- contact force estimation & control (anywhere/anytime)
Collision or collaboration?

- **hard/accidental collisions**
- **soft/intentional contacts**

distinguished with a frequency analysis of a model-based signal ("residual")

Claudio Gaz, Emanuele Magrini, Alessandro De Luca

Dipartimento di Ingegneria Informatica, Automatica e Gestionale, Sapienza Università di Roma

May 2017
... also on conventional industrial robots

intentional contacts and/or collisions may occur anywhere

6-dof **KUKA KR5 Sixx** with a closed control architecture and RSI interface at $T_c = 12$ ms
Robots as job killers?

Jobs lost... Jobs gained

Source: Fortune
Poche occupazioni sono interamente automatizzabili, anche se il 60% di tutte le occupazioni hanno almeno il 30% delle loro attività che sono automatizzabili (già con le attuali tecnologie).

<table>
<thead>
<tr>
<th>Esempi di occupazione</th>
<th>Accumulo percentuale (%)</th>
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</thead>
<tbody>
<tr>
<td>addetto macchine tessili, selezionatore di prodotti agricoli</td>
<td>100% = 820 tipi di occupazione considerati, con oltre 2000 attività elementari</td>
</tr>
<tr>
<td>magazziniere, agente di viaggi, riparatore di orologi</td>
<td></td>
</tr>
<tr>
<td>tecnico chimico, aiuto infermiere, sviluppatore web</td>
<td></td>
</tr>
<tr>
<td>disegnatore di moda, amministratore delegato, statistico</td>
<td></td>
</tr>
<tr>
<td>psichiatra, legislatore</td>
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</table>

Menos del 5% delle occupazioni consiste in attività automatizzabili al 100%.

In circa il 60% delle occupazioni si può automatizzare almeno il 30% di attività elementari.
Diversi settori, diversi mix di attività, diversa automazione ...

Potenziale tecnologico di automazione (%)

Attività

attività fisiche ripetitive
elaborazione di dati
raccolta di dati
attività fisiche variabili
interfaccia con clienti/utenti
attività decisionali, di pianificazione e creative
gestione e sviluppo di risorse umane

Settori produttivi

A. De Luca – HRC – Saperi
Robots and humans

A future where robots are more social than solitary

Robots will enhance human work and life rather than replace us in our homes, hospitals, factories, farms and freeways

From Information & Communication Technology (ICT) to InterAction Technology (IAT)
From Internet of Things (IoT) to Internet of Skills (IoS)
Roboethics

Ethical, legal and societal issues for design, construction and use of robots

Cohabitation of humans with robots
Next generation of intelligent robots?

Robots = embodied AI systems

Robotics = science of artifacts intelligently actuated and interacting with the real world

AI

cognitive robotics

physical AI

mechanics, electronics, hydraulics, ...

system identification (data-driven), adaptation, learning

model-based techniques, dynamic primitives, uncertainty

Control Engineering

robot motion and interaction control

A. De Luca – HRC – Saperi
References

- research papers (open in IRIS)
  - [http://www.diag.uniroma1.it/deluca/Publications.php](http://www.diag.uniroma1.it/deluca/Publications.php)

- YouTube channel **DIAG Robotics Lab** with our research videos
  - [www.youtube.com/user/RoboticsLabSapienza](http://www.youtube.com/user/RoboticsLabSapienza)
  - see in particular the playlist: Physical Human-Robot Interaction

- web sites of courses
  - Robotics 1 [www.diag.uniroma1.it/deluca/rob1_en](http://www.diag.uniroma1.it/deluca/rob1_en)
  - Robotics 2 [www.diag.uniroma1.it/deluca/rob2_en](http://www.diag.uniroma1.it/deluca/rob2_en)

- YouTube channel **Video DIAG - Sapienza**
  - [www.youtube.com/channel/UCbaID7wz_ATPrddPkJYVK1w](http://www.youtube.com/channel/UCbaID7wz_ATPrddPkJYVK1w)
  - playlist **Robotics 1**: video-lectures 2014-15
  - playlist **Robotics 2**: video-lectures 2019-20

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