



# Computer vision for non-rigid object assembly automation

With applications in automotive wire harness assembly

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Chalmers University of Technology

# We interact with objects every day

Rigid object



Non-rigid object

# The same challenge appears in manufacturing

Rigid, structured tasks are easier to automate



Source: <https://www.pexels.com/>



Source: <https://www.pexels.com/>



Source: <https://www.pexels.com/>



Source: <https://if.org/if-press-releases/news/one-million-robots-work-in-car-industry-worldwide-new-record>



Source: <https://www.pexels.com/>



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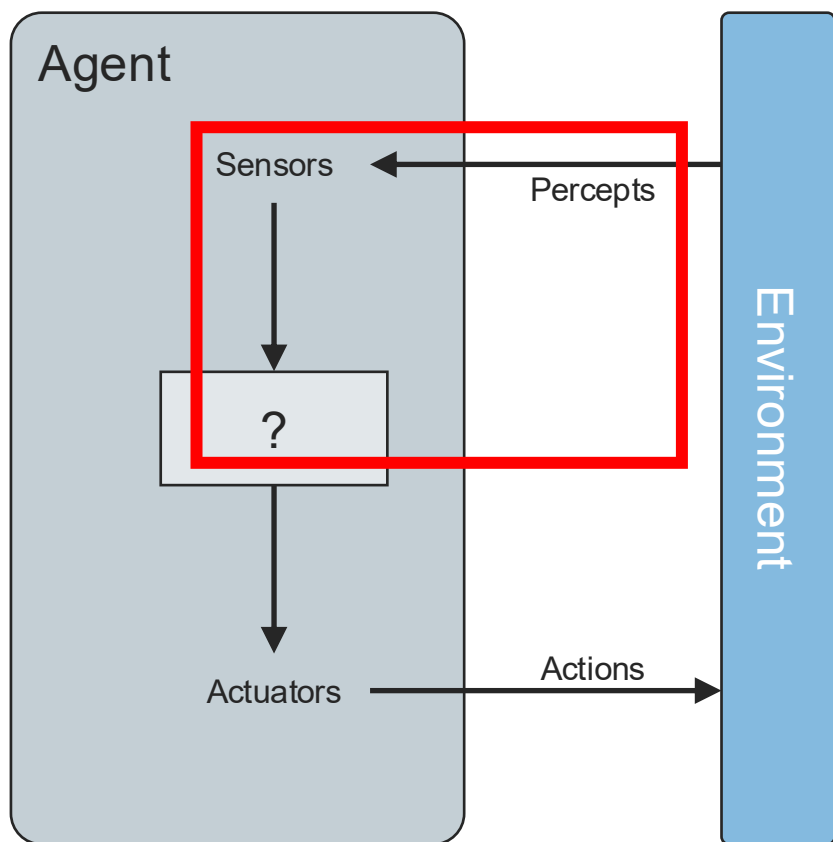
Source: <https://www.assemblymag.com/articles/96864-wiring-harness-manufacturers-face-three-big-challenges-in-2022>



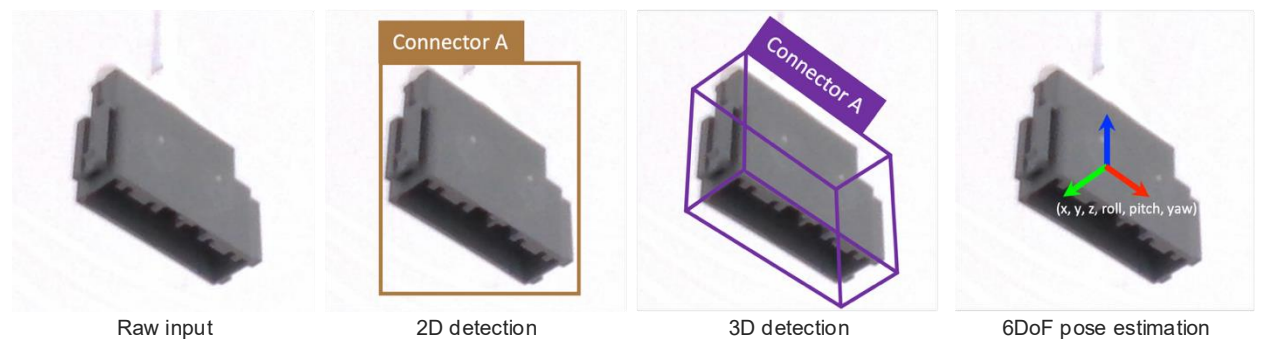
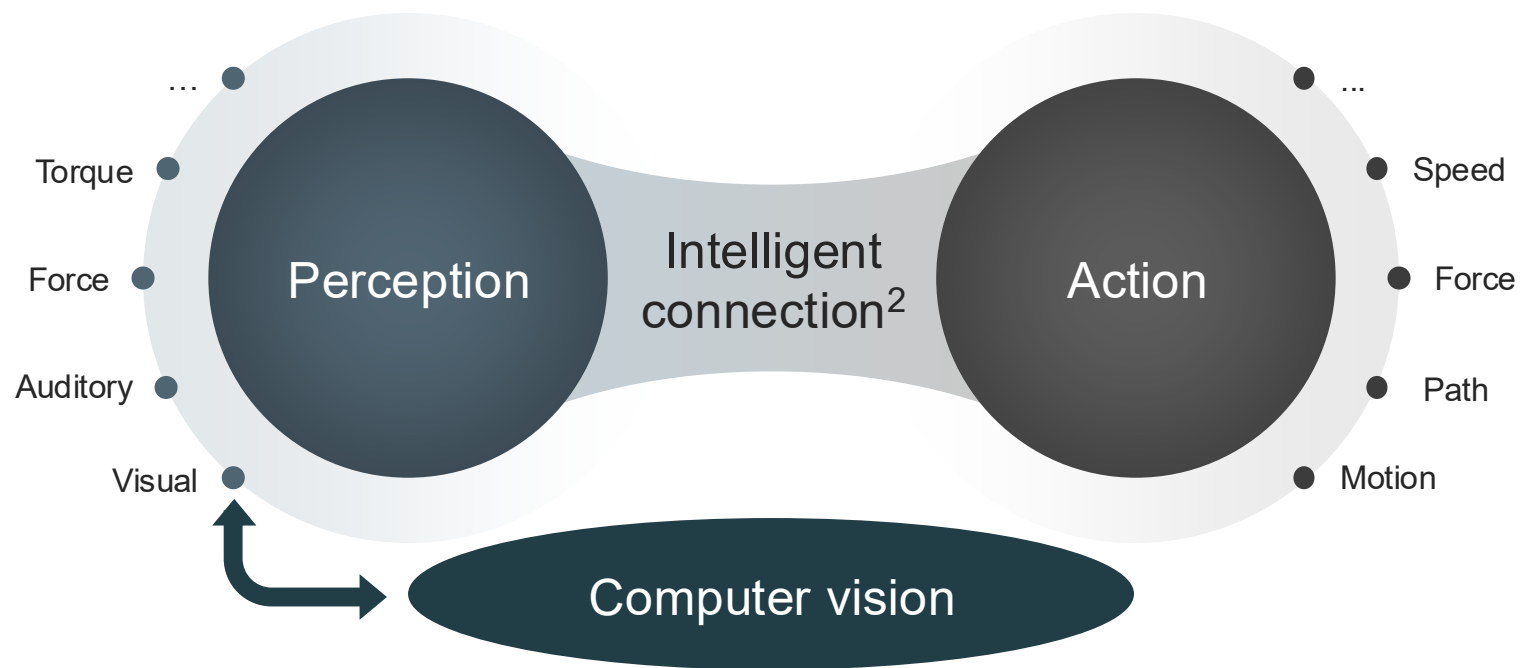
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Flexible, deformable objects create more uncertainty

# Perception is crucial



Agents interact with environments through sensors and actuators.<sup>1</sup>



<sup>3</sup>

<sup>1</sup>S. J. Russell and P. Norvig, "Intelligent agents," in *Artificial intelligence: a modern approach*, 4th ed., Pearson series in artificial intelligence, Pearson, 2021, ch. 2, pp.36–62.

<sup>2</sup>M. Brady, "Artificial intelligence and robotics," *Artificial Intelligence*, vol. 26, no. 1, pp. 79–121, 1985.

<sup>3</sup>R. Li and H. Qiao, "A survey of methods and strategies for high-precision robotic grasping and assembly tasks—some new trends," *IEEE/ASME Transactions on Mechatronics*, vol. 24, no. 6, pp. 2718–2732, 2019.



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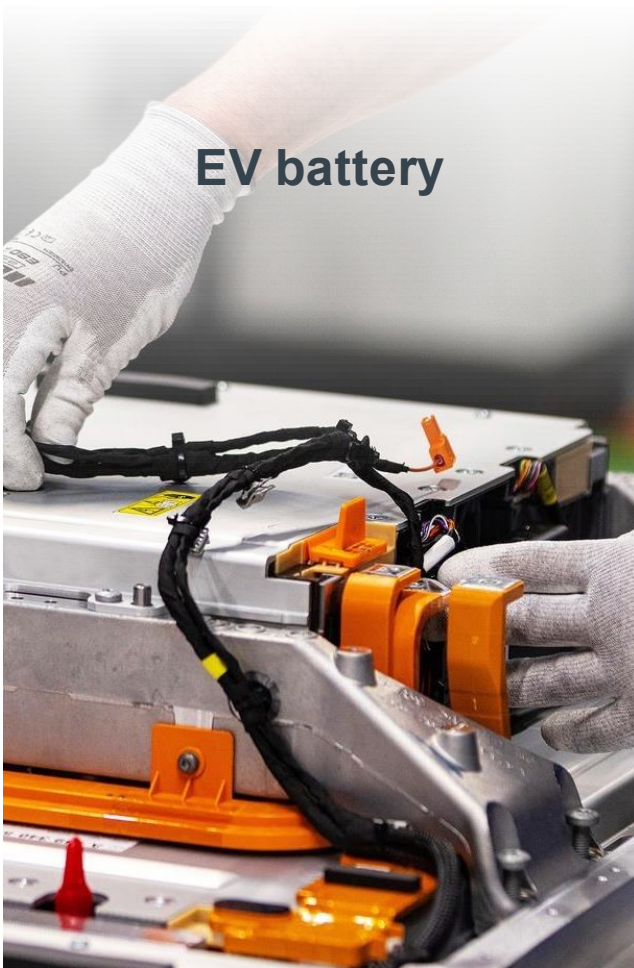
Chalmers University of Technology

Gothenburg, Sweden

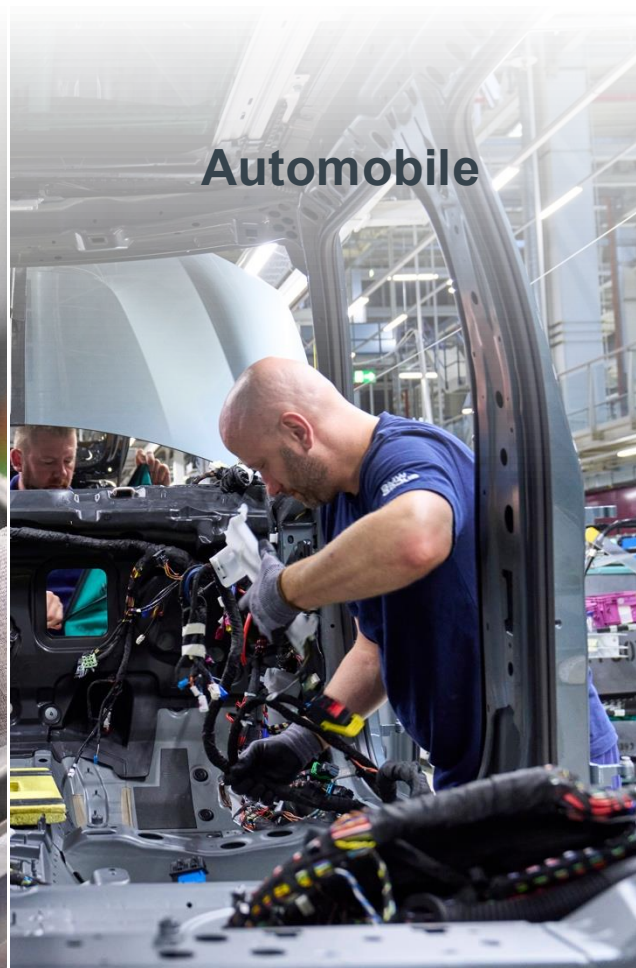
June 2, 2026

# Why wire harness assembly?

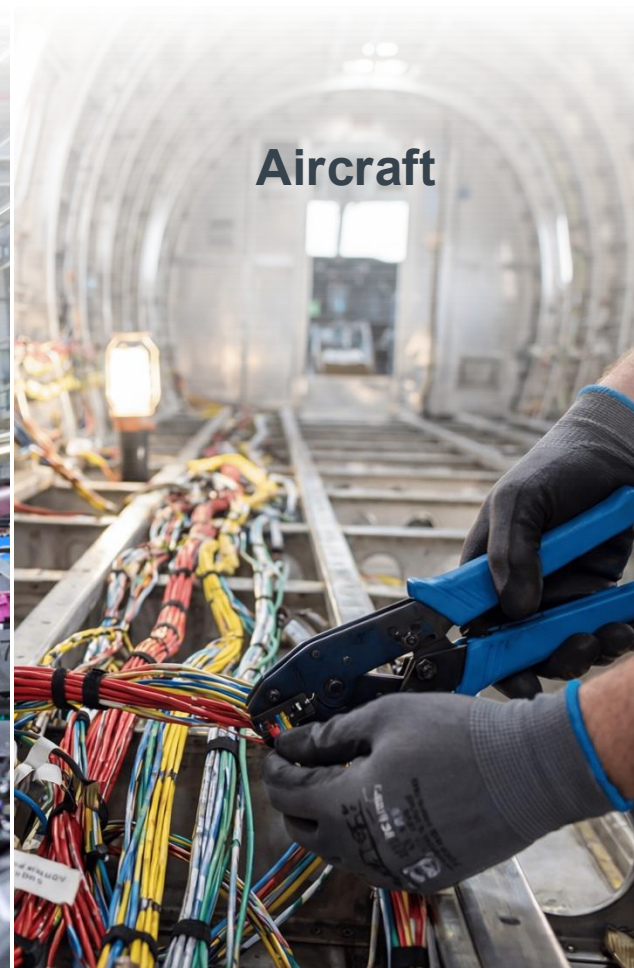
Wire harnesses are widely utilized in products with electrical systems, such as automobiles, aircraft, and consumer electronics<sup>1</sup>.



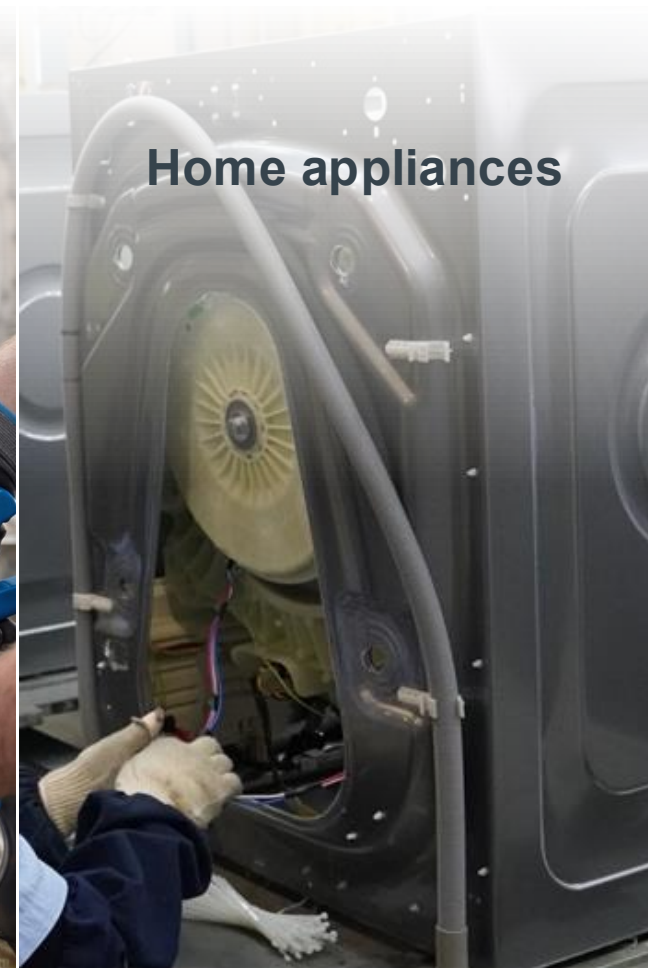
**EV battery**



**Automobile**



**Aircraft**



**Home appliances**

Source: <https://www.wired.com/story/ev-battery-fires-explained>

Source: <https://www.press.bmwgroup.com/global/photo/compilation/T0438210EN/one-line-%E2%80%93-two-brands-%E2%80%93-three-drives-bmw-group-plant-lapzig-launches-production-of-the-mini-countryman>

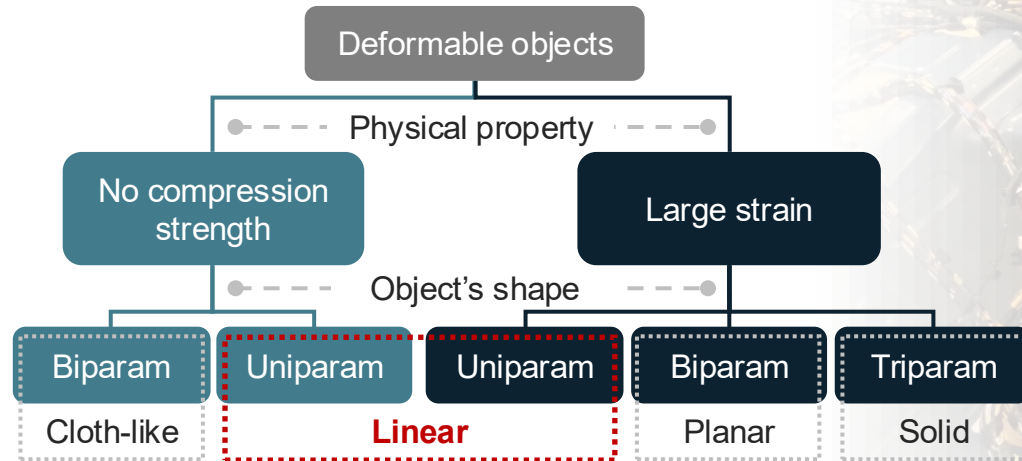
Source: <https://meemsdb.com/blog/aircraft-wiring-electrical-system-parts-mro-procurement-guide>

Source: <https://www.taqi-robot.com/washingmachineassy>

<sup>1</sup>G. E. Navas-Reascos, D. Romero, J. Stahre and A. Caballero-Ruiz, "Wire harness assembly process supported by collaborative robots: Literature review and call for r&d," *Robotics*, vol. 11, no. 3, p. 65, 2022.

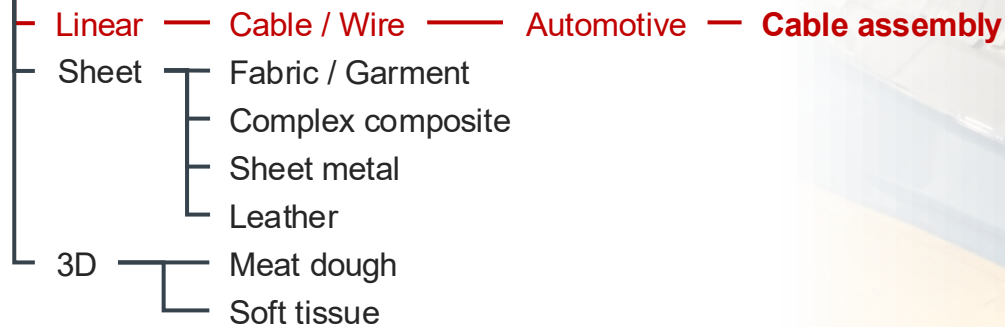
# Why wire harness assembly?

Wire harness assembly exemplifies deformable linear object (DLO) manipulation<sup>1</sup> and non-rigid object assembly<sup>2</sup>.



Classification of deformable objects<sup>1</sup>

## Industrial classification of flexible material manipulation applications<sup>3</sup>



<sup>1</sup>J. Sanchez, J.-A. Corrales, B.-C. Bouzgarrou, and Y. Mezouar, "Robotic manipulation and sensing of deformable objects in domestic and industrial applications: A survey," *The International Journal of Robotics Research*, vol. 37, no. 7, pp. 688–716, 2018.

<sup>2</sup>S. Makris, F. Dietrich, K. Kellens and S. J. Hu, "Automated assembly of non-rigid objects," *CIRP Annals*, vol. 72, no. 2, pp. 513–539, 2023.

<sup>3</sup>M. Saadat and P. Nan, "Industrial applications of automatic manipulation of flexible materials," *Industrial Robot: An International Journal*, vol. 29, no. 5, pp. 434–442, 2002.

# Why is automation needed?

The current manual wire harness assembly is problematic in terms of productivity, quality, safety, and ergonomics<sup>1</sup>.



Volkswagen. Source: <https://www.youtube.com/watch?v=R2G5SL3Xrdw>



Skoda. Source: <https://www.youtube.com/watch?v=Tr1B18XJ8Z8>

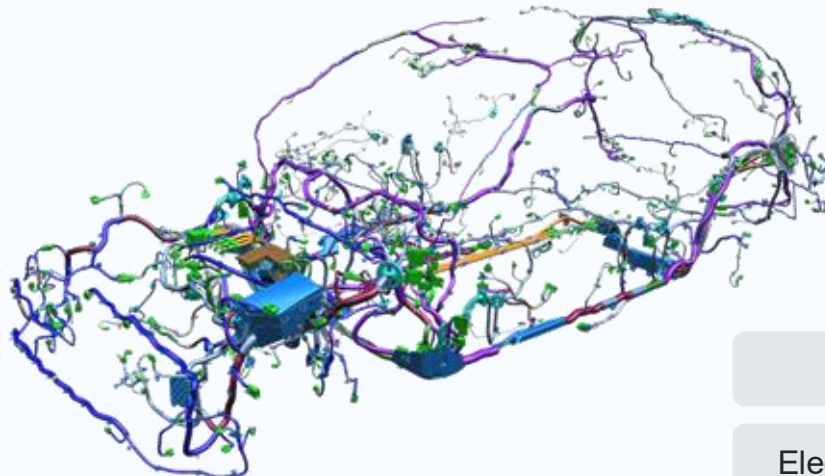


Tesla. Source: <https://www.youtube.com/watch?v=QF6H0qT4J0>



Volvo Cars. Source: [https://www.youtube.com/watch?v=4T5TKzrv\\_ds](https://www.youtube.com/watch?v=4T5TKzrv_ds)

## Essential infrastructure



Signal

Electric current

The electrical infrastructure of a Volvo XC 40 Recharge. Source: Volvo Car Corporation.

## Increasing usage and growing market<sup>2</sup>



Year 2000  
1000 m



Year 2003  
1500 m



Year 2008  
2000 m



Year 2020  
2800 m

The heavily increasing length of wires in passenger cars over years. Source: Volvo Car Corporation.

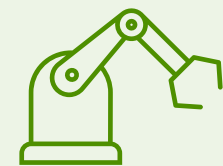
### Current operations

- Manual
- Repetitive
- Skill-demanding

### Problems<sup>1</sup>

- Quality
- Productivity
- Safety
- Ergonomics

### Robotic assembly<sup>3</sup>



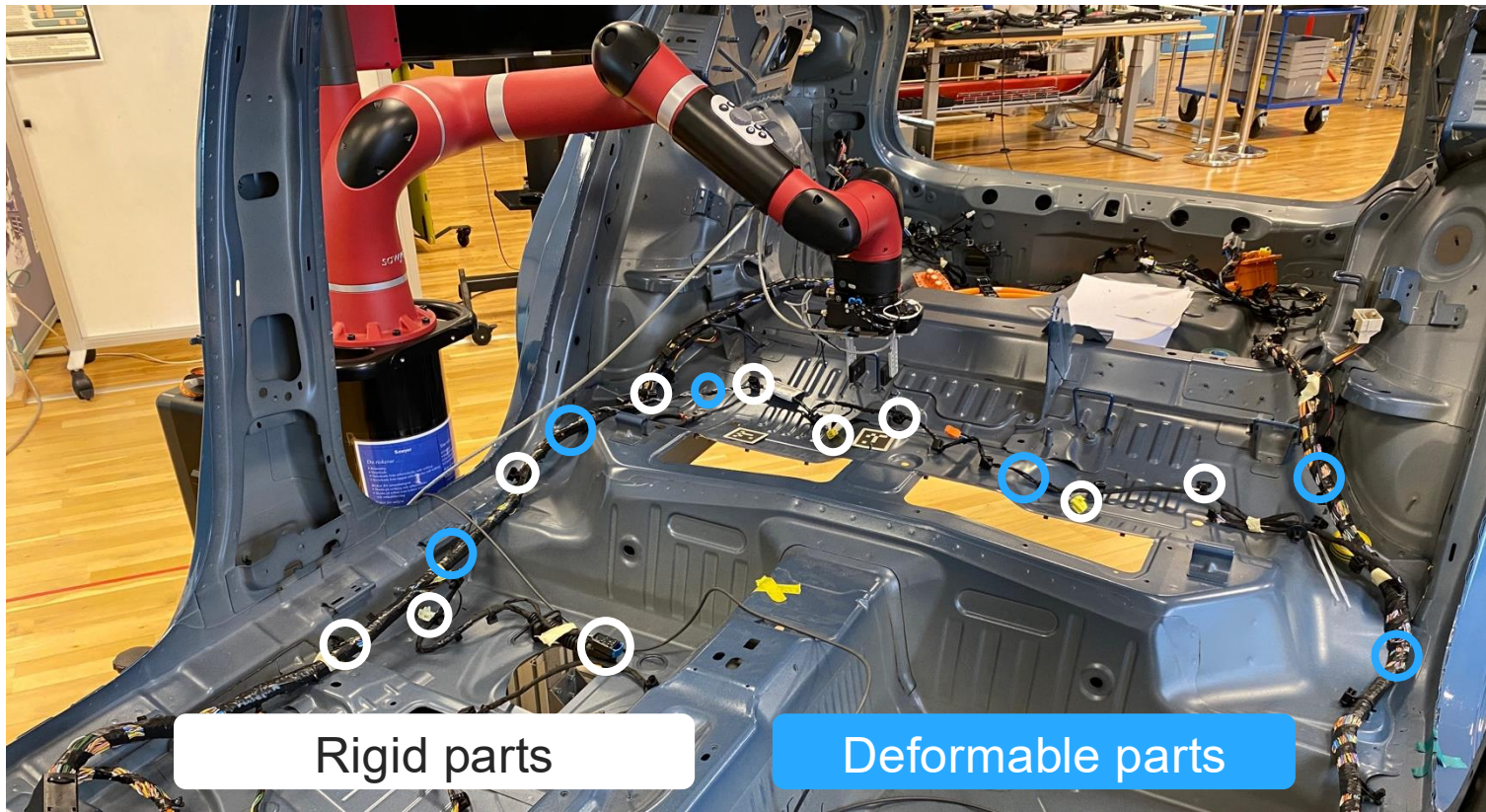
<sup>1</sup>X. Jiang, K-m. Koo, K. Kikuchi, A. Konno and M. Uchiyama, "Robotized assembly of a wire harness in a car production line," *Advanced Robotics*, vol. 25, no. 3-4, pp. 473-489, 2011.

<sup>2</sup>Strategic Market Research, "Automotive wiring harness market By material (copper, aluminum, others), by vehicle type (passenger cars, two-wheelers, commercial vehicles), by application (chassis harness, engine harness, body & lighting harness, dashboard/ cabin harness, sunroof harness, battery harness, hvac harness, seat harness, door harness), by geography, size, global share, forecast, 2021-2030," Strategic Market Research, Tech. Rep., 2022.

<sup>3</sup>G. Michalos, S. Makris, N. Papakostas, D. Mourtzis and G. Chryssodouris, "Automotive assembly technologies review: Challenges and outlook for a flexible and adaptive approach," *CIRP Journal of Manufacturing Science and Technology*, vol. 2, no. 2, pp. 81-91, 2010.

# Why is computer vision needed?

Vision is instrumental for object recognition and localization<sup>1</sup>, and computer vision enables contactless robotic perception<sup>2</sup>.



Rigid parts

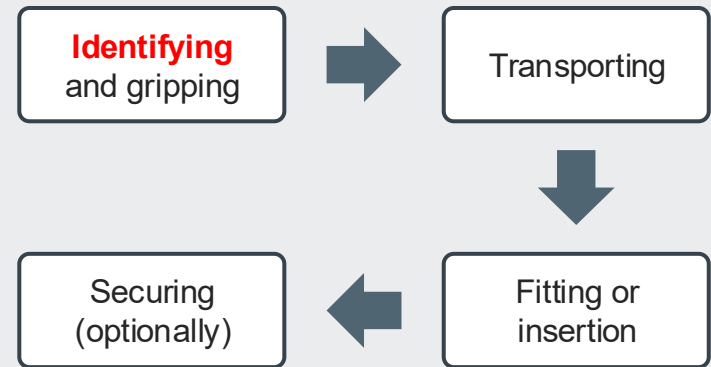
Deformable parts

Unstructured task and environment

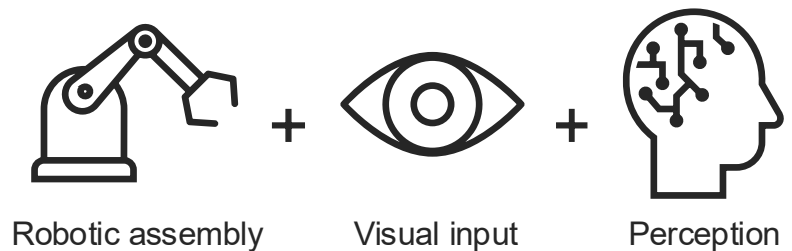
Impossible to pre-program<sup>3</sup>

Requiring higher dexterity and adaptability<sup>4</sup>

## Sub-procedures of assembly tasks<sup>5</sup>



“Vision is instrumental for recognizing and localizing objects.”<sup>1</sup>



<sup>1</sup>A. Billard and D. Kragic, "Trends and challenges in robot manipulation," *Science*, vol. 364, no. 6446, eaat8414, 2019.  
<sup>2</sup>M. Brady, "Artificial intelligence and robotics," *Artificial Intelligence*, vol. 26, no. 1, pp. 79–121, 1985.  
<sup>3</sup>S. Makris, F. Dietrich, K. Kellens and S. J. Hu, "Automated assembly of non-rigid objects," *CIRP Annals*, vol. 72, no. 2, pp. 513–539, 2023.  
<sup>4</sup>G. Michalos, S. Makris, N. Papakostas, D. Mourtzis and G. Chryssodouris, "Automotive assembly technologies review: Challenges and outlook for a flexible and adaptive approach," *CIRP Journal of Manufacturing Science and Technology*, vol. 2, no. 2, pp. 81–91, 2010.  
<sup>5</sup>T. K. Lien, "Manual assembly," in *CIRP Encyclopedia of Production Engineering*, Springer, 2014, pp. 825–828

# Vision, aim, and research questions

## Vision

A future manufacturing industry characterized by **high efficiency** and **sustainability**, with **minimal operational disruptions**.

- Robots perform non-value-adding and ergonomically challenging tasks.
- Robots flexibly adapt to various tasks and dynamic production scenarios.

## Aim

Proposing **technical solution** using **computer vision** to facilitate **robotic automation** for non-rigid object assembly tasks.

- Wire harness assembly is industrially relevant and inherently complex.
- The proposed approaches are designed to be generalizable.

## Research questions

1. What are the challenges in applying computer vision to wire harness assembly automation?
2. How can computer vision be applied to wire harness assembly automation?

Enable robotic visual perception

Improve the autonomy of industrial robots

Make industrial robots competent in non-predefined tasks

Promote the symbiosis of humans and robots

Achieve highly efficient, problem-free, sustainable production



Robotic assembly

+



Visual input

+



Perception

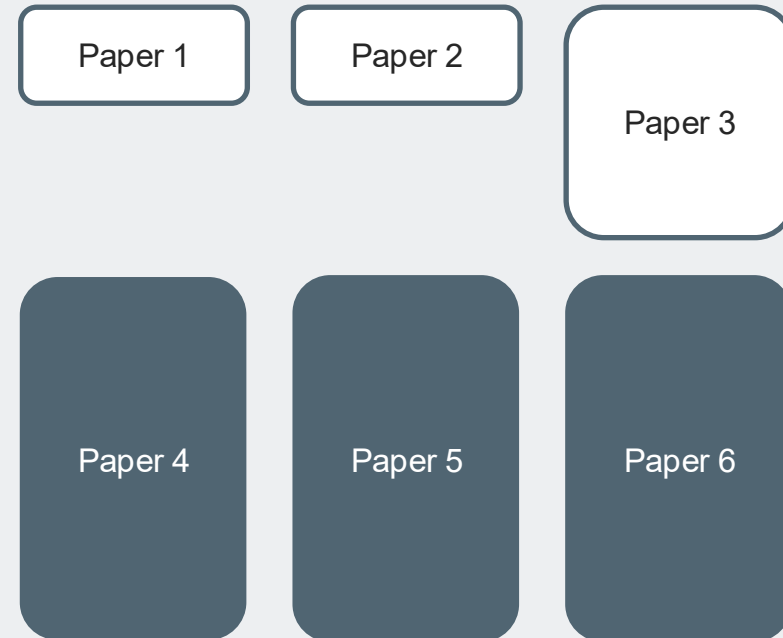
# Research design

This thesis incorporates positivist research design<sup>1</sup>, design science research (DSR)<sup>2</sup>, and multiple methods design<sup>3</sup>.

## Design science research methodology<sup>4</sup>



## Multiple methods design<sup>3</sup>



Qualitative

Quantitative

<sup>1</sup>K. Williamson, F. Burstein and S. McKernish, "The two major traditions of research," in *Research methods for students, academics and professionals*, ser. Topics in Australasian Library and Information Studies, 2nd ed., Chandos Publishing, 2002, ch. 2, pp. 25-47.

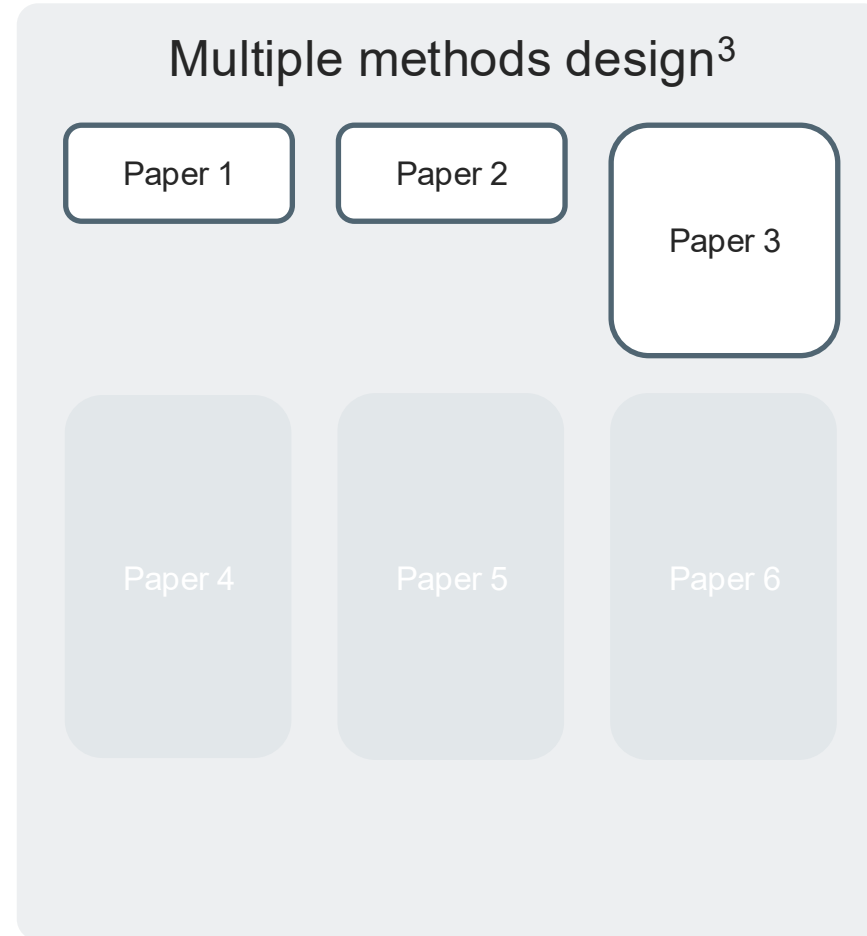
<sup>2</sup>A. Hevner and S. Chatterjee, "Design science research in information systems," in *Design Research in Information Systems: Theory and Practice*, ser. Integrated Series in Information Systems, vol. 22, Springer, 2010, ch. 2, pp. 9-22.

<sup>3</sup>J. Morse, "Procedures and practice of mixed method design: Maintaining control, rigor, and complexity," in *Sage handbook of mixed methods in social & behavioral research*, 2nd ed., SAGE Publications, Inc., 2010, ch. 14, pp. 339-352.

<sup>4</sup>K. Peffers, T. Tuunanen, M. A. Rothenberger and S. Chatterjee, "A design science research methodology for information systems research," *Journal of management information systems*, vol. 24, no. 3, pp. 45-77, 2007.

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# Why computer vision and HRC matter

Paper 1 (Section 3.1): Automation and human–robot collaboration (HRC) for human-centric production in complex manufacturing<sup>1</sup>

## Industrial challenges

- Variant-rich production
  - Increasing **product customization**
  - Greater **product and process variability**
- Conventional automation is often **too rigid** for complex assembly

## Why computer vision

- Perception as an enabler
  - Agile automation requires stronger **robotic perception**
  - Robotic perception enables **context-aware** and **safer** robot operation
  - Computer vision supports **object recognition** and **scene understanding**

## Why HRC

- **Human-centered** deployment
  - Full automation is **not always practical**
  - HRC **combines** robot repeatability with human adaptability
  - Computer vision supports **safe** and **efficient close-proximity** collaboration

Complex, variant-rich manufacturing requires both stronger perception and human-centered integration.

# Why wire harness assembly automation is hard

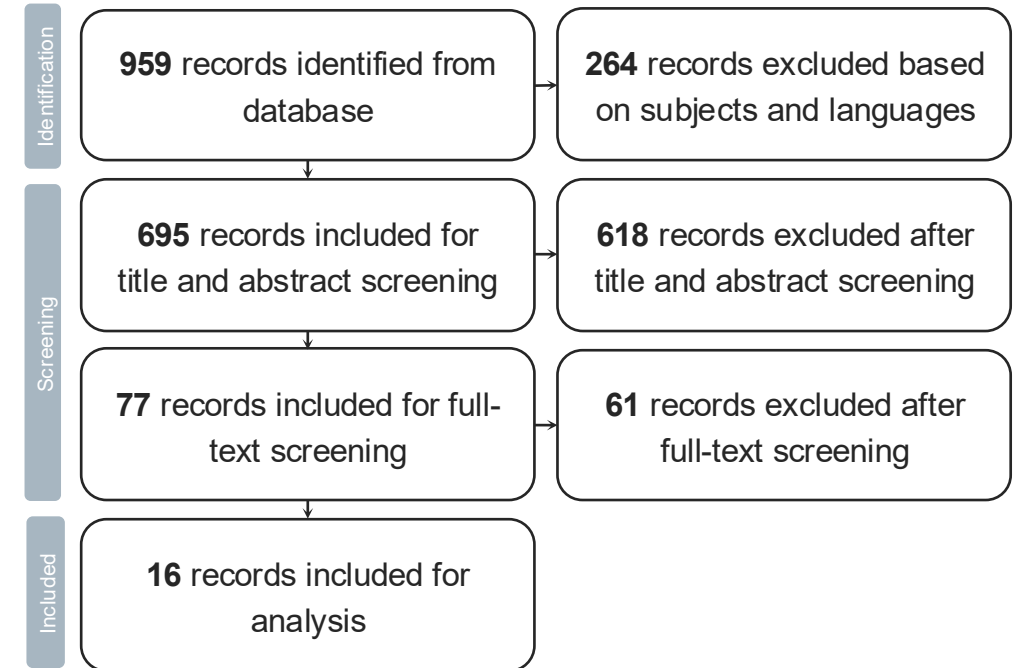
Paper 2: Review of current status and future directions for wire harnesses assembly automation<sup>1</sup>

## Purpose and aim of this study

- Review the current state of wire harness assembly automation
- Identify future directions, especially for collaborative and semi-automated solutions

Review criteria	
Database	Scopus
Search string	(wir* OR cabl*) AND (harness* OR bundl*) AND assembl*
Search field	Article title, Abstract, Keywords
Subject area	Engineering; Computer Science; Multidisciplinary; Business, Management and Accounting; Decision Sciences
Article language	English
Search date	August 8, 2022

Note. This table is adapted from Section 2.1 of Paper 2.



Note. PRISMA<sup>2</sup> flow diagram adapted from Fig. 1 of Paper 2.

Existing solutions were **fragmented** and **not yet widely deployable**.

1

**Collaborative** and **semi-automated** assembly appear promising.

2

**Vision systems** are important for guidance, monitoring, safety, and quality assurance.

3

# What are the challenges for computer vision?

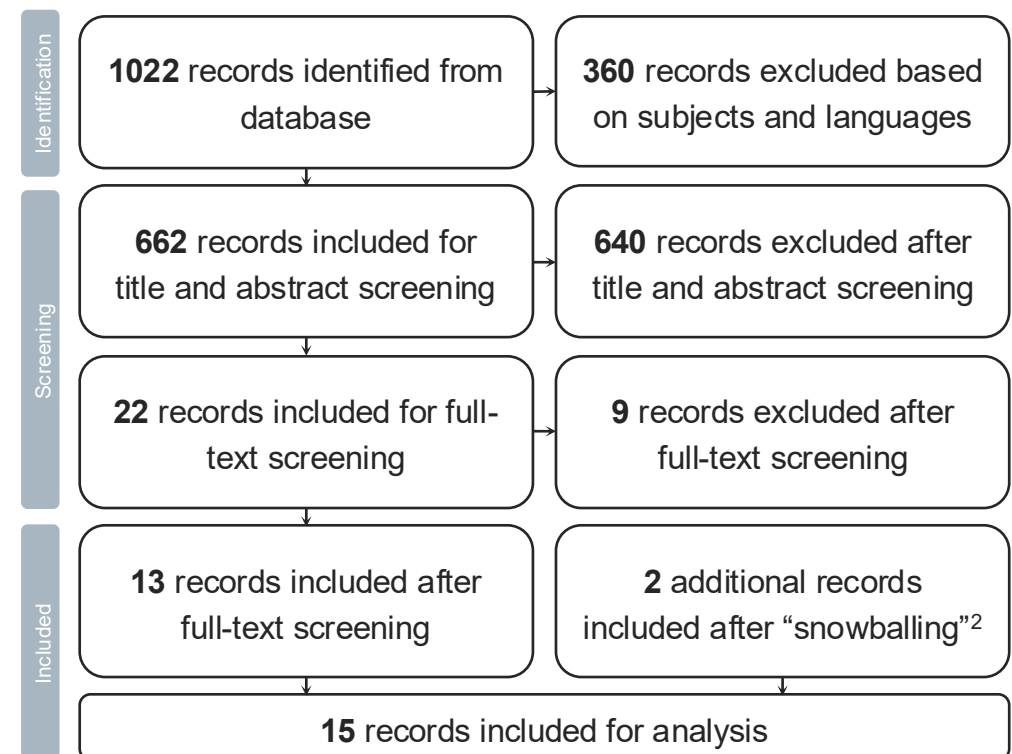
Paper 3: A systematic literature review of computer vision applications in robotized wire harness assembly<sup>1</sup>

## Research questions guiding the systematic literature review

- What computer vision-based solutions have been proposed for robotized wire harness assembly?
- What are the challenges for computer vision applications in robotized wire harness assembly?
- What are the required future research activities and fields for developing more efficient and practical computer vision-based robotized wire harness assembly?

Review criteria	
Database	Scopus
Search string	(wir* OR cabl*) AND (harness* OR bundl*) AND assembl*
Search field	Article title, Abstract, Keywords
Subject area	Engineering; Computer Science; Multidisciplinary; Business, Management and Accounting; Decision Sciences
Article language	English
Inclusion criteria	Proposing computer vision-based algorithm and/or technology for robotized wire harness assembly
Exclusion criteria	Not about wire harnesses; not about robotic assembly; about the manufacturing of wire harnesses
Search date	September 6, 2023

Note. This table is adapted from the Table 1 of Paper 3.



Note. PRISMA<sup>3</sup> flow diagram adapted from Fig. 4 of Paper 3.

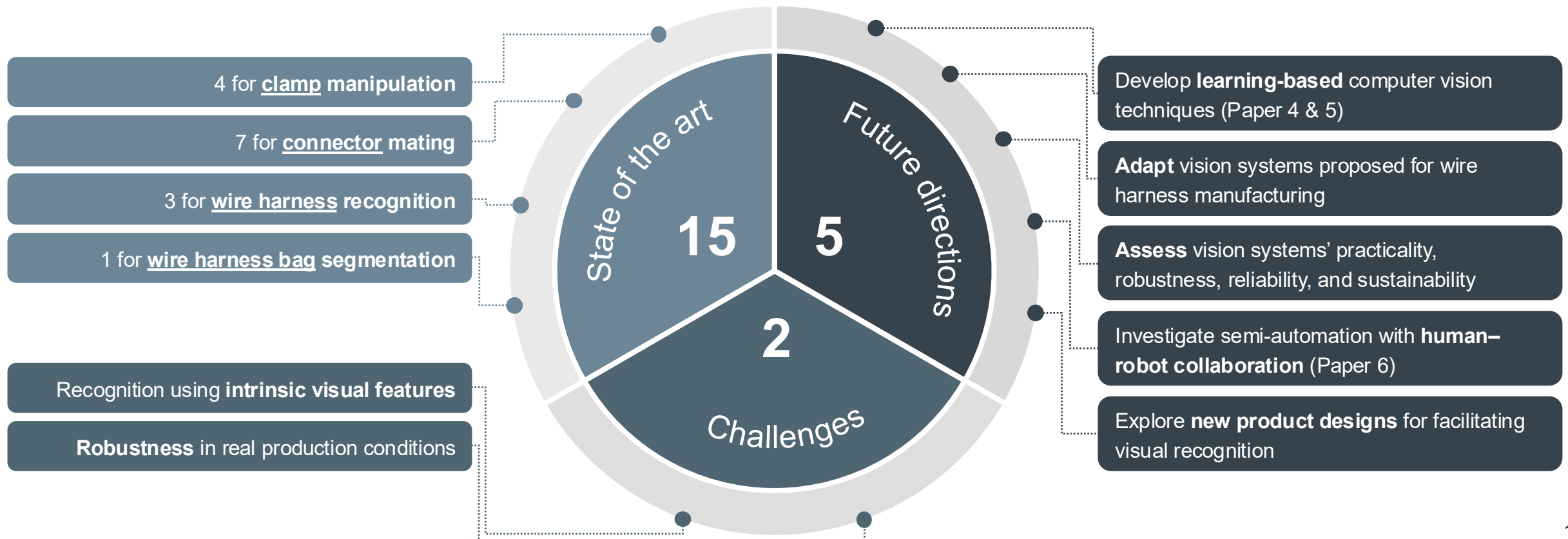
<sup>1</sup>H. Wang et al., "A systematic literature review of computer vision applications in robotized wire harness assembly," *Advanced Engineering Informatics*, vol. 62, p. 102596, 2024.  
<sup>2</sup>T. Greenhalgh and R. Peacock, "Effectiveness and efficiency of search methods in systematic reviews of complex evidence: Audit of primary sources," *BMJ*, vol. 331, no. 7524, pp. 1064–1065, 2005.  
<sup>3</sup>M. J. Page et al., "The PRISMA 2020 statement: an updated guideline for reporting systematic reviews," *BMJ*, vol. 372, n71, 2021.

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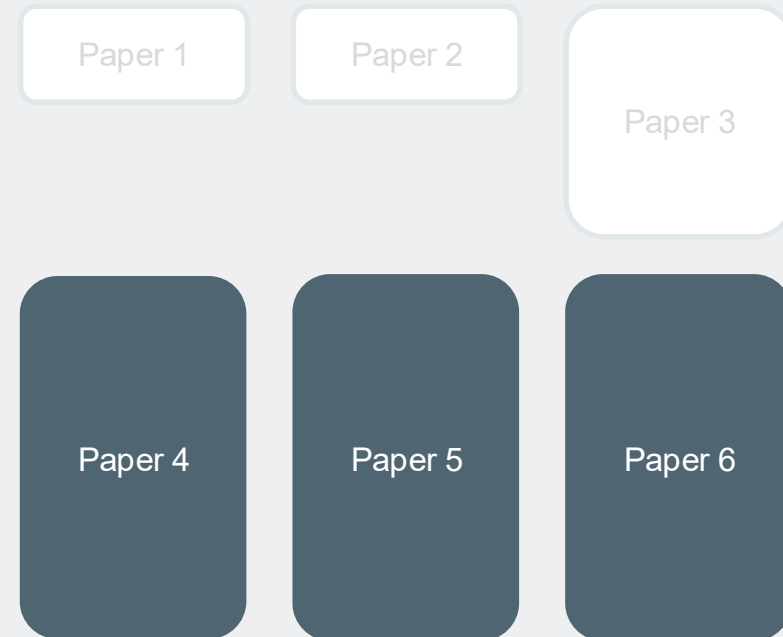
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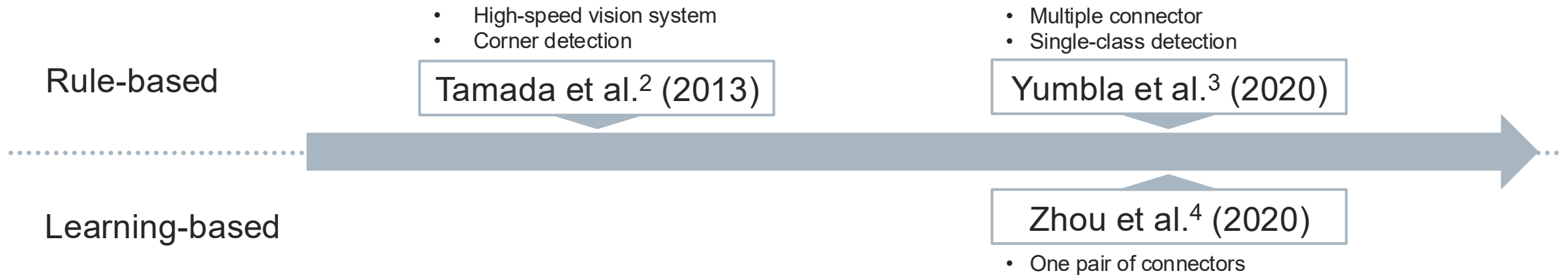
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<sup>4</sup>K. Peffers, T. Tuunanen, M. A. Rothenberger and S. Chatterjee, "A design science research methodology for information systems research," *Journal of management information systems*, vol. 24, no. 3, pp. 45-77, 2007.

# How feasible is deep learning-based detection?

Paper 4: Deep learning-based multi-class wire harness connector detection<sup>1</sup>



- Are generic deep learning-based object detectors effective on multi-class connector detection?
- What are the potential obstacles for learning-based multi-class connector detection?

<sup>1</sup>H. Wang and B. Johansson, "Deep learning-based connector detection for robotized assembly of automotive wire harnesses," in *2023 IEEE 19th International Conference on Automation Science and Engineering (CASE)*, 2023, pp. 1–8.

<sup>2</sup>T. Tamada, Y. Yamakawa, T. Senoo, and M. Ishikawa, "High-speed manipulation of cable connector using a high-speed robot hand," in *2013 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, 2013, pp. 1598–1604.

<sup>3</sup>F. Yumbla, M. Abeyabas, T. Luong, J.-S. Yi, and H. Moon, "Preliminary connector recognition system based on image processing for wire harness assembly tasks," in *2020 20th International Conference on Control, Automation and Systems (ICCAS)*, 2020, pp. 1146–1150.

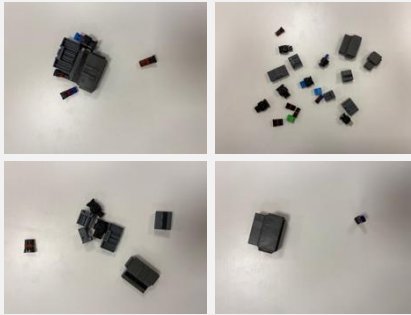
<sup>4</sup>H. Zhou, S. Li, Q. Lu, and J. Qian, "A practical solution to deformable linear object manipulation: A case study on cable harness connection," in *2020 5th International Conference on Advanced Robotics and Mechatronics (ICARM)*, 2020, pp. 329–333.

# How feasible is deep learning-based detection?

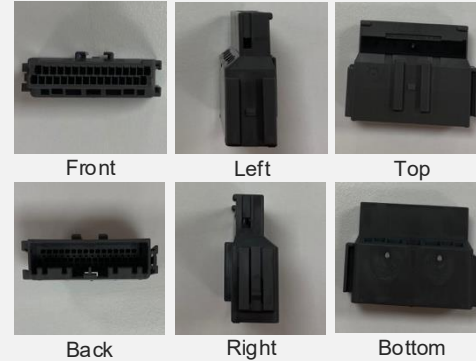
Paper 4: Deep learning-based multi-class wire harness connector detection<sup>1</sup>

## 360 images in total

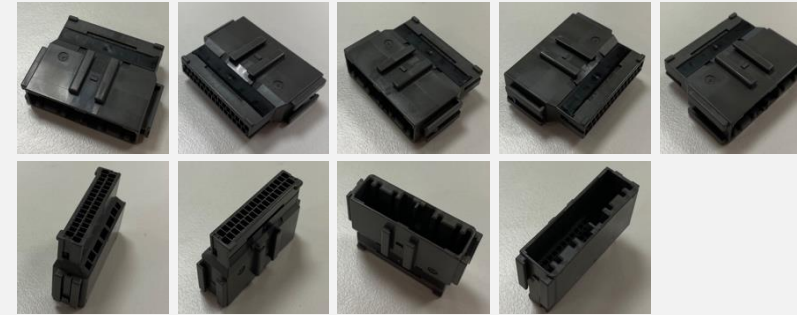
- Mixed (60 images)



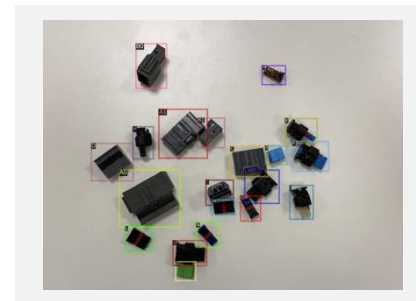
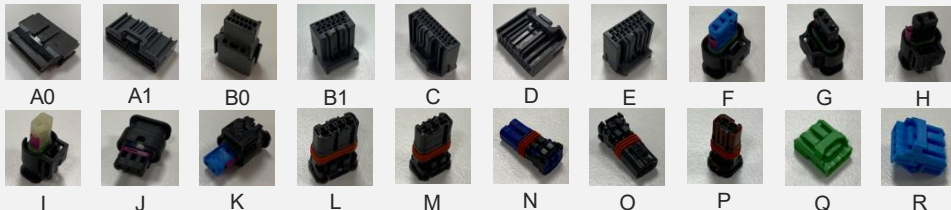
- Profile (6 images/connector)



- Random-view (9 images/connector)



## 20 wire harness connectors



- Two-stage detector:** Faster RCNN<sup>2</sup>
- One-stage detector:** YOLOv5<sup>3</sup>
- Metric**
  - Precision rate
  - mAP

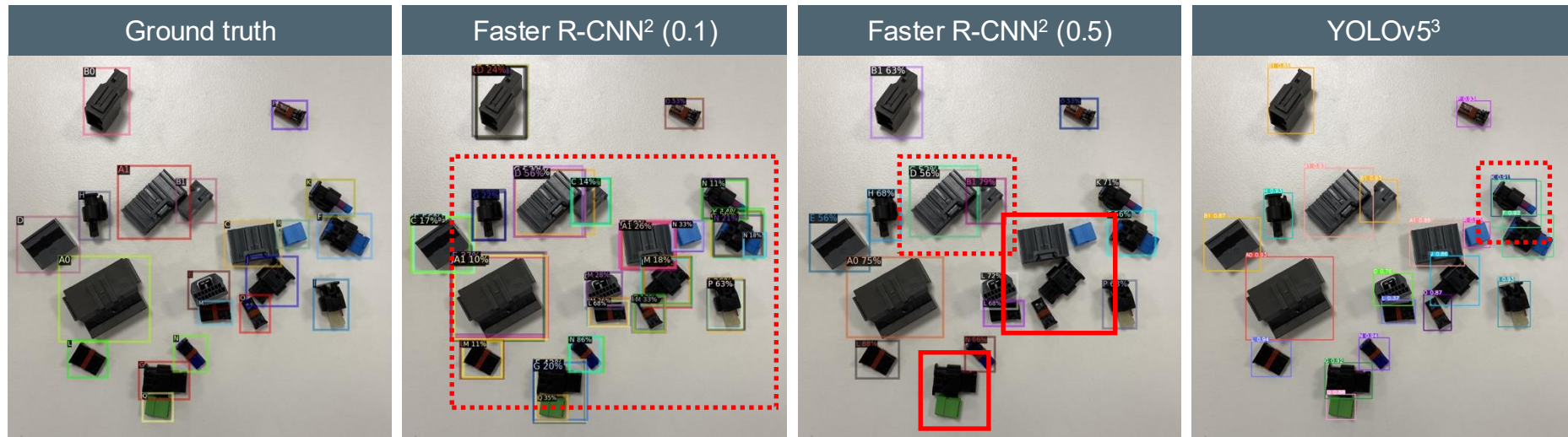
<sup>1</sup>H. Wang and B. Johansson, "Deep learning-based connector detection for robotized assembly of automotive wire harnesses," in *2023 IEEE 19th International Conference on Automation Science and Engineering (CASE)*, 2023, pp. 1–8.

<sup>2</sup>S. Ren, K. He, R. Girshick and J. Sun, "Faster r-cnn: Towards real-time object detection with region proposal networks," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 39, no. 6, pp. 1137–1149, 2017.

<sup>3</sup>G. Jocher, *Yolov5 by Ultralytics*, version 7.0, 2020.

# How feasible is deep learning-based detection?



Paper 4: Deep learning-based multi-class wire harness connector detection<sup>1</sup>



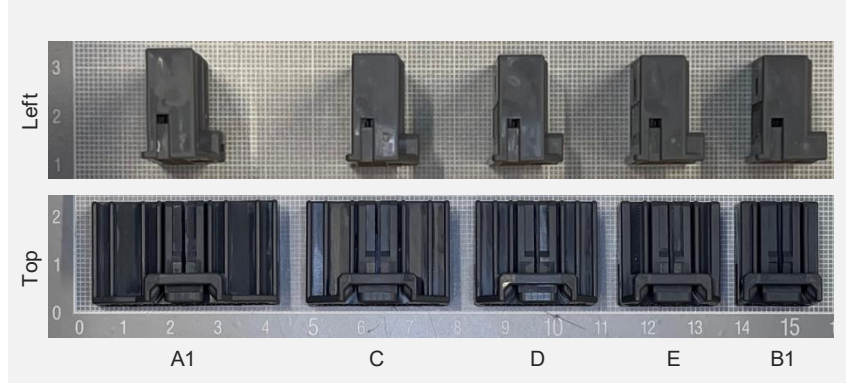
Deep learning-based methods are effective

- Both types of object detection methods are effective
- One-stage YOLOv5-based model performs better

Problematic detection exists

- Missing 
- Overlapping 
- Potentially affected by current product designs

Highly similar features



Heavily occluded features



Future work

- Better detection algorithms
- More training data
- New product design for vision

<sup>1</sup>H. Wang and B. Johansson, "Deep learning-based connector detection for robotized assembly of automotive wire harnesses," in *2023 IEEE 19th International Conference on Automation Science and Engineering (CASE)*, 2023, pp. 1–8.  
<sup>2</sup>S. Ren, K. He, R. Girshick and J. Sun, "Faster r-cnn: Towards real-time object detection with region proposal networks," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol. 39, no. 6, pp. 1137–1149, 2017.  
<sup>3</sup>G. Jocher, *Yolov5 by Ultralytics*, version 7.0, 2020.

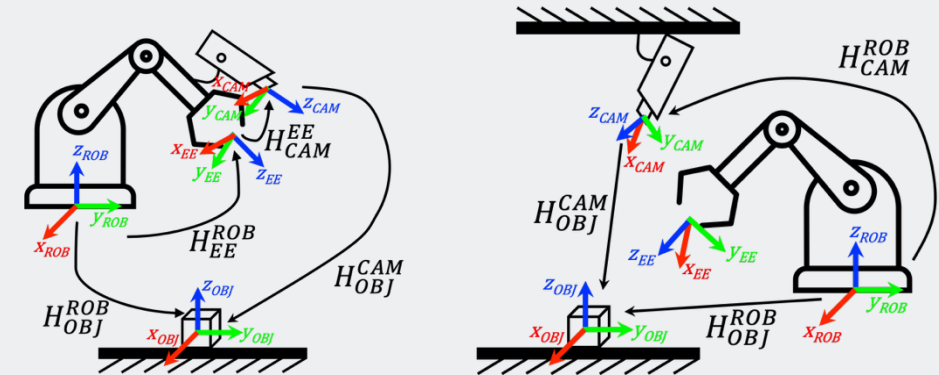
# How to automate and scale dataset preparation?

Paper 5: Accelerating robot vision dataset preparation with collaborative robotic automation<sup>1</sup>

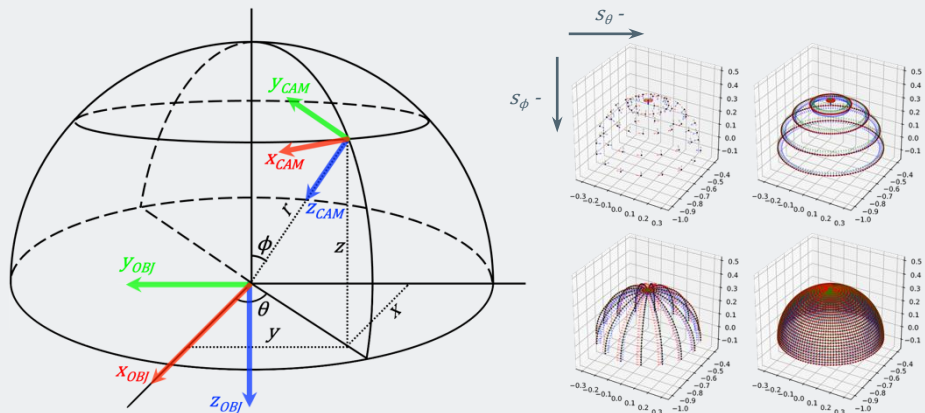
## Problems in existing data collection methods

- **Manual data collection**
  - Labor-intensive, time-consuming, and demands specialized expertise<sup>2</sup>
- **Synthetic data generation**
  - Simulation-to-reality gap<sup>3</sup>
  - Requires domain-specific modeling and real-world validation
- **Real-world data collection**
  - Gantry-based methods typically involves complex and costly acquisition setups<sup>4</sup>
  - Robot-assisted methods generally lack a systematic, scalable pipeline<sup>5</sup>

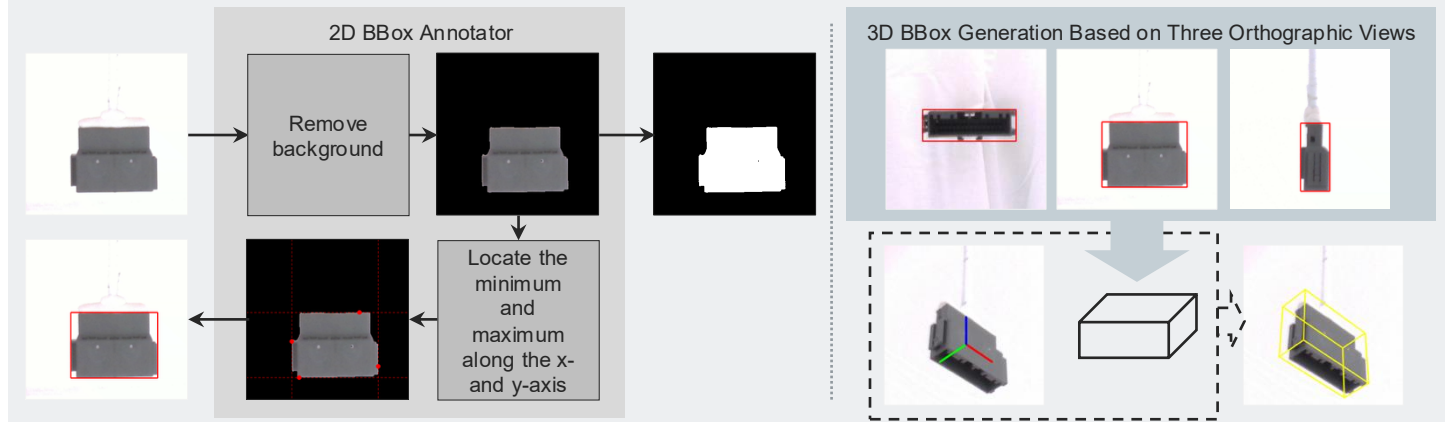
## Robotic data acquisition



## Systematic observation pose generation



## Automatic data annotation



<sup>1</sup>H. Wang, G. Urbanos Uribe, K. El-Nahass, S. Ekered and B. Johansson, "Accelerating industrial vision: Systematic robot-assisted dataset preparation for object detection and pose estimation," *Engineering Applications of Artificial Intelligence*, vol. 176, p. 114741, 2026.

<sup>2</sup>M. Gyögi and Vittorio Ferrari, "Efficient object annotation via speaking and pointing," *International Journal of Computer Vision*, vol. 128, no. 5, pp. 1061–1075, 2020.

<sup>3</sup>N. Jakobi, P. Husbands and I. Harvey, "Noise and the reality gap: The use of simulation in evolutionary robotics," in *Advances in Artificial Life*, 1995, pp. 704–720.

<sup>4</sup>A. Singh, J. Sha, K. S. Narayan, T. Achim and P. Abbeel, "Bigbird: A large-scale 3d database of object instances," in *2014 IEEE International Conference on Robotics and Automation (ICRA)*, 2014, pp. 509–516.

<sup>5</sup>P. Koch, M. Schlüter, S. Thill and Jörg Krüger, "Towards robot-assisted data generation with minimal user interaction for autonomously training 6d pose estimation in operational environments," *Procedia CIRP*, vol. 120, pp. 249–254, 2023.

# How to automate and scale dataset preparation?

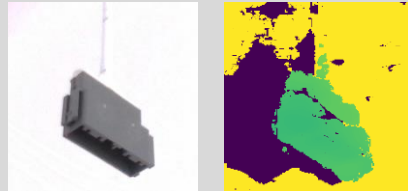
Paper 5: Accelerating robot vision dataset preparation with collaborative robotic automation<sup>1</sup>

## The proposed robot-assisted data collection pipeline

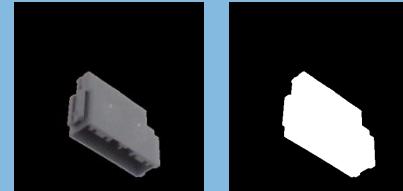
1. A human fixes an object at the pre-defined position (in this case, pointed by the red arrow)



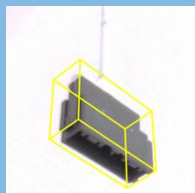
2. The robot moves the camera to a new observation pose to capture RGB-D data



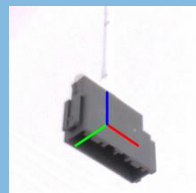
3. Remove the background to obtain the object mask based on the captured RGB-D data



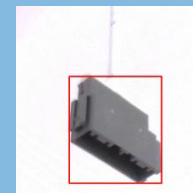
6. Generate the 3D BBox label based on the generated 2D BBox and 6DoF object pose labels of the front-, top-, and left-view data



5. Generate the 6DoF pose label based on the observation pose and generated 2D BBox label



4. Generate the 2D BBox label based on the object mask



## Evaluation config.

**Robot:** UR5 (Universal Robots)  
**Camera:** D435 (Intel RealSense)  
**Object:** 20 connectors  
**Step size of  $\theta(s_\theta)$ :**  $\pi/8$   
**Step size of  $\phi(s_\phi)$ :**  $\pi/8$   
**Number of viewpoints:** 80

**2.390**

seconds per image acquisition

**0.254**

seconds per image annotation

**150**

times faster than fully manual workflow approximately

# How can computer vision enable HRC?

Paper 6: Vision-based human-robot collaboration (HRC) for wire harness assembly in automotive manufacturing<sup>1</sup>

## Problems in manual wire harness assembly

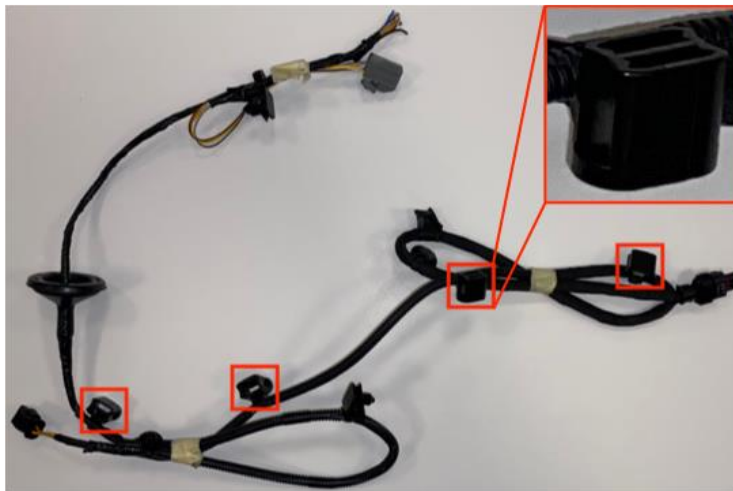
- Repetitive, force-intensive operations
- Ergonomically challenging gestures

## Challenges for robotic wire harness assembly

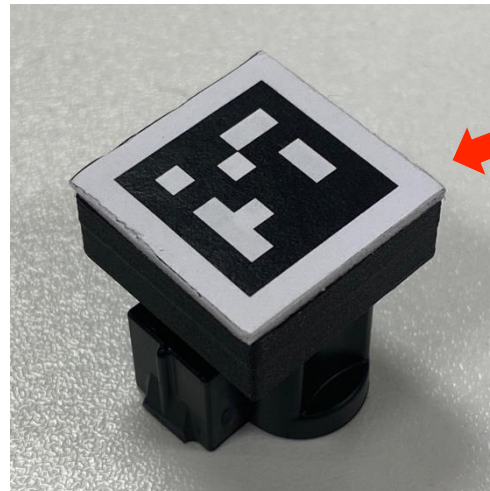
- Complex motion sequences and influence due to part geometry, tolerances, and contact interactions<sup>2</sup>
- Perception, modeling, and control when involving non-rigid objects<sup>3</sup>

## Human-robot collaboration

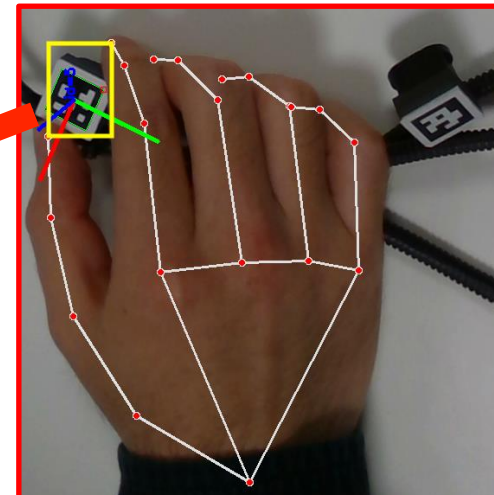
- Robot performs **repetitive, force-intensive** operations
- Human manages tasks requiring **dexterity and quality assessment**
- Vision system **recognize** target parts and **guide** robot's movement



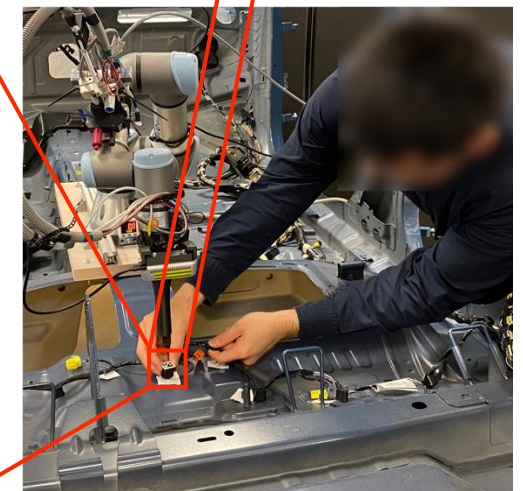
Automotive wire harnesses



ArUco-based pose estimation



Hand-triggered robot control



Two-phase experiments

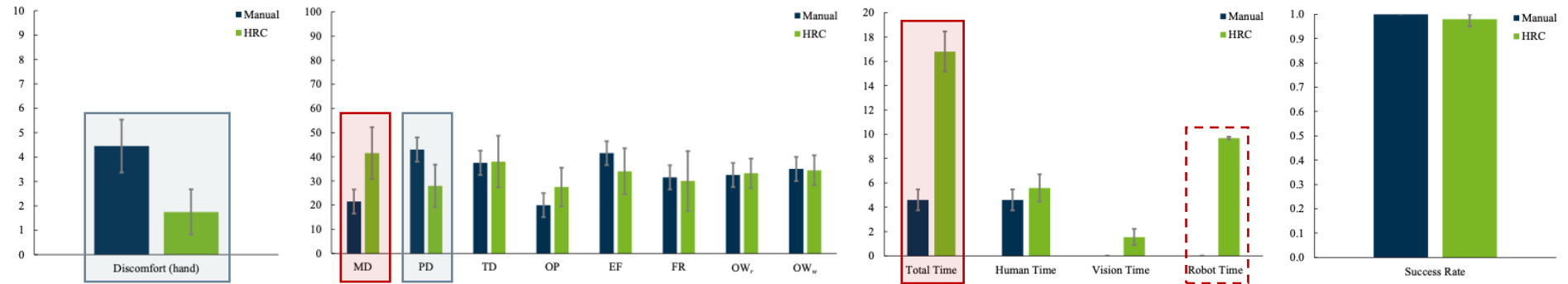
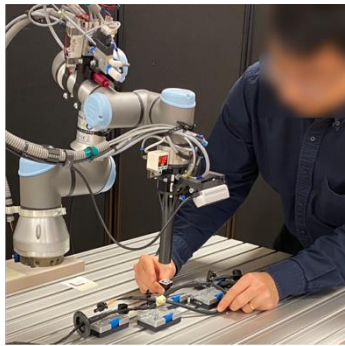
<sup>1</sup>H. Wang et al., "Vision-based human-robot collaboration for wire harness assembly in automotive manufacturing," *Submitted to a scientific journal (under revision)*, 2026.  
<sup>2</sup>J. Heyn, P. Gümbel, P. Bobka, F. Dietrich and K. Dröder, "Application of artificial neural networks in force-controlled automated assembly of complex shaped deformable components," *Procedia CIRP*, vol. 79, pp. 131–136, 2019.  
<sup>3</sup>H. Yin, A. Varava and D. Kragic, "Modeling, learning, perception, and control methods for deformable object manipulation," *Science Robotics*, vol. 6, no. 54, p. eabd8803, 2021

# How can computer vision enable HRC?

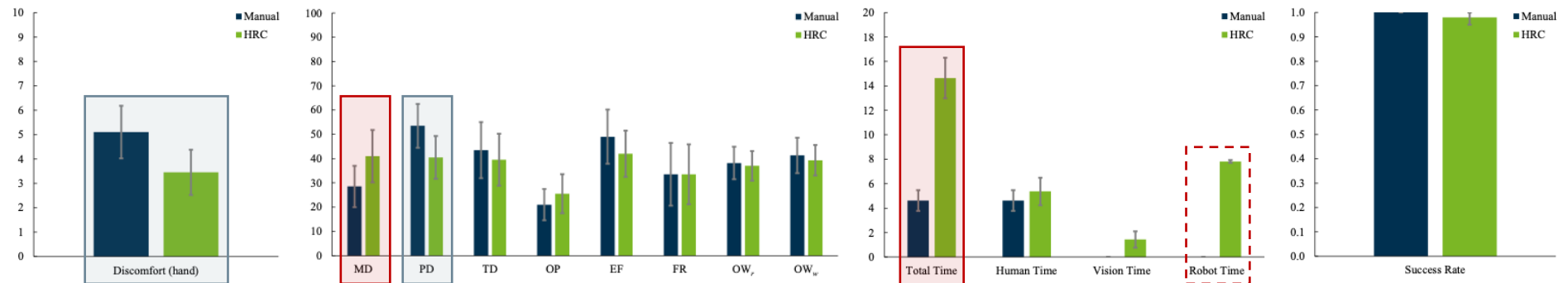
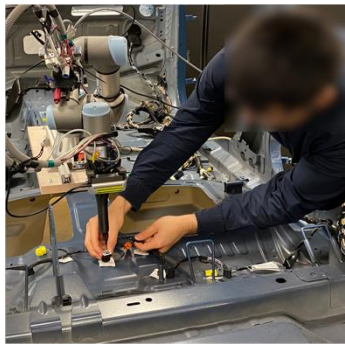
Paper 6: Vision-based human-robot collaboration (HRC) for wire harness installation in automotive manufacturing<sup>1</sup>

## Experiment: A vision-based HRC system for automotive wire harness installation

### ➤ In laboratory environment (TRL<sup>2</sup> 4)



### ➤ In relevant environment (TRL<sup>2</sup> 5–6)



Vision-based HRC can improve ergonomics, but its practical use depends on reducing cognitive burden and improving robot-side efficiency.

<sup>1</sup>H. Wang et al., "Vision-based human-robot collaboration for wire harness assembly in automotive manufacturing," *Submitted to a scientific journal (under revision)*, 2026.  
<sup>2</sup>J. C. Mankins, "Technology readiness assessments: A retrospective," *Acta Astronautica*, vol. 65, no. 9, pp 1216-1223, 2009.

# Answers to RQ1

What are the challenges in applying computer vision to wire harness assembly automation?



## • Rigid parts

- Small, low-texture, visually similar
- Hard to detect and estimate 6DoF pose

## • Deformable parts

- Changing shape and branched topology
- Hard to recognize and track

Object complexity

Data scarcity



- Few domain-specific **datasets**
- Manual **annotation** is slow and costly
- Limits **scalability** of learning-based methods
- Need automated, scalable **dataset preparation**

Robust deployment  
requires visual  
perception that is  
accurate, scalable,  
efficient, and  
production-ready.

Scene variability

Operational constraints

## • Occlusion and clutter

- Variable **lighting**
- Confined **workspaces**
- Restricted **camera placement** / limited **viewpoints**



## • Takt-time requirements

- **Safety** in collaborative settings
- **Robustness** and **context-awareness**
- **Generalizability** across variants and environments

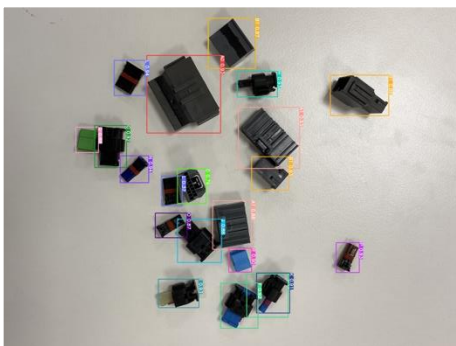


# Answers to RQ2

How can computer vision be applied to wire harness assembly automation?

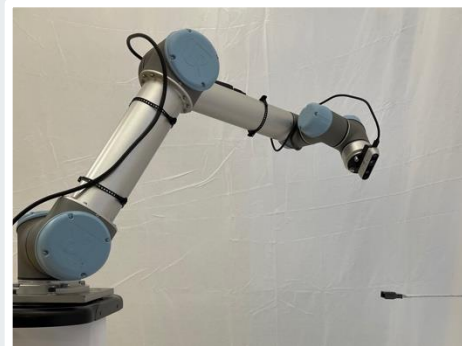
## Learning-based visual recognition

- **Markerless** detection and 6DoF pose estimation
- **More robust** computer vision algorithms
  - Multi-view
  - Multimodal
  - Video-based



## Automated dataset preparation

- Robot-assisted multi-view acquisition
- Automated multimodal annotation
- **Scalable support** for learning-based development



## Vision-based human-robot collaboration

- Localize objects and monitor operator actions
- Enable safe, context-aware robot execution
- Improve ergonomics and task flexibility



## Industrial validation

- Test under real-world production conditions
- Assess **robustness, reliability, and scalability**
- Advance toward production-ready solutions



# Research contributions



## To academia

### Structured challenge map

Identify challenges at the **object, scene, data,** and **operational** levels

### Research roadmap

Consolidates the **state of the art** and identifies **future research directions**

### Validated technical contributions

Advances **learning-based detection, 6DoF pose estimation,** and **vision-based HRC**

### Data-centric contribution

Proposes **robot-assisted dataset preparation** and contributes a **connector dataset**

## Barriers and solutions

## To industry

### Practical implementation guidance

**Workflows** for data collection, model training, evaluation, and HRC integration

### Maturity advancement

Progresses key technologies from early-stage concepts toward **TRL 4–6** (detection ~4; dataset pipeline ~6; HRC ~6)

### Design and process recommendations

Highlights the impact of **product design, workspace conditions,** and **production constraints**

### Cost-effective dataset preparation

Demonstrates **scalable, robot-assisted dataset preparation** for industrial vision

This thesis bridges computer vision research and real-world deployment in complex, non-rigid object assembly automation.

# Research limitations



- Focused on **automotive wire harnesses** in **passenger vehicle cabins**
- Studied key **subtasks**
  - Connector mating
  - Clamp insertion
- Does **not cover full end-to-end wire harness assembly**

## Research scope

## Validation scale

- Deep learning-based detection and pose estimation on **20** connector types
- HRC validated in lab and industrially relevant settings
- **Not yet tested on production lines in operation**

- Mainly on rigid components:
  - Connectors
  - Clamps
- Partially on deformable cable segments
- Transfer to other DLO tasks remains unvalidated

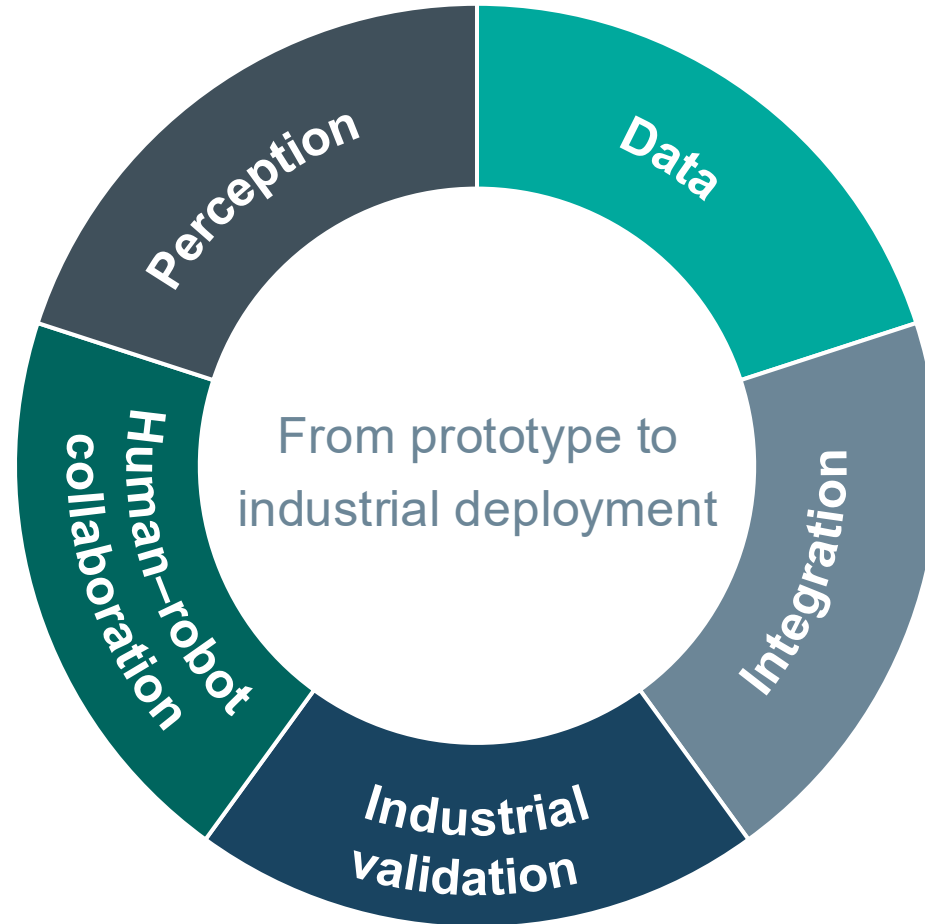
## Technical contribution

## Contextual boundary

- Primarily reflects **automotive final assembly**
- Strongest relevance to the **Swedish passenger vehicle production** context
- Adaptation likely needed for other industries and production settings

# Future work

From promising component-level prototypes to robust, end-to-end, production-ready vision systems for non-rigid object assembly automation



- Improve **recognition of small, texture-less, occluded components**
- Combine **multi-view, multimodal, and uncertainty-aware perception**
- **Optimize** both accuracy and latency

- Expand reusable **datasets** across components and conditions
- Add **tasks** beyond detection and pose estimation
- Combine **real + synthetic data** for scalable development

- Improve **human action / intention recognition**
- **Reduce cognitive load** and **improve task fluency**
- **Extend** collaborative automation to more assembly steps

- Move from isolated functions to **full assembly sequences**
- Add **anomaly detection** and **recovery behaviors**
- Study **cumulative error propagation** across steps

- **Validate** under production variability and takt-time constraints
- **Integrate** safety, traceability, and maintainability
- **Transfer** methods to other non-rigid object assembly tasks

# Summary and conclusion

The research examines computer vision as a critical enabler for robotic automation of non-rigid object assembly, with wire harness assembly in automotive final assembly as the primary application.

## Identified challenges

- **Non-rigid object assembly remains hard** because of:
  - Complex topology
  - High variability
  - Frequent occlusion
  - Small, texture-less components
- **Industrial deployment also requires:**
  - Robustness
  - Reliability
  - Practicality

## Developed technologies

- **Validated learning-based perception** for detection and pose estimation of wire harness components
- **Developed a robot-assisted dataset preparation pipeline** for scalable multi-view acquisition and automated multimodal annotation
- **Demonstrated vision-based human-robot collaboration** for wire harness installation with ergonomic benefits

## Implications

- **Markerless learning-based vision** is feasible, but depends on **high-quality domain data**
- **Robot-assisted dataset preparation** makes industrial vision development more scalable
- **Vision-based collaboration** is promising, but cycle time and cognitive load remain important **trade-offs**

Computer vision is most effective today as a human-centered integrator of robust perception, scalable data generation, and collaborative workflow under industrial constraints.



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# Thank you!



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