Licentiate Seminar

May 16, 2024

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Toward Enabling Robotic Visual Perception for Assembly Tasks

An Application in Wire Harness Assembly onto Electric Vehicles

Hao Wang

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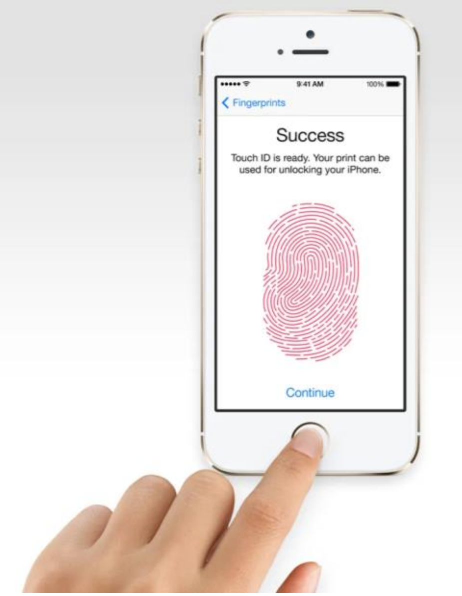
Gothenburg, Sweden, 2024

Discussion leader: Prof. Tauno Otto

Examiner: Prof. Johan Stahre
Main supervisor: Prof. Björn Johansson
Co-supervisor: Prof. Anders Skoogh

Automation Driven by Artificial Intelligence and Computer Vision

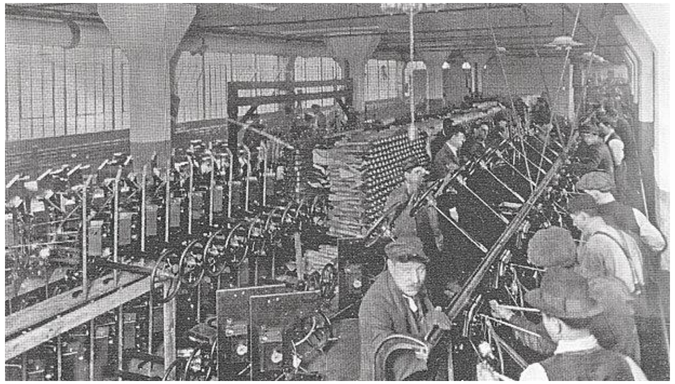
Automation - “the conversion of a procedure, a process, or equipment to an automatic operation without intervention by a human operator”[1]



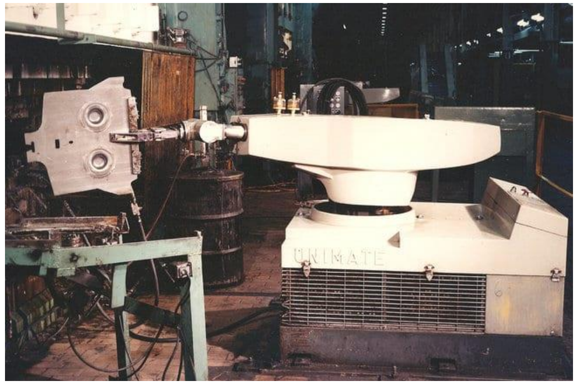
TouchID. Figure Credit: iTnews. https://www.itnews.com.au/news/iphone-6-vulnerable-to-touchid-fingerprint-hack-392414

FaceID. Figure Credit: MakeUseOf. https://www.makeuseof.com/tag/iphone-x-face-id-downsides/

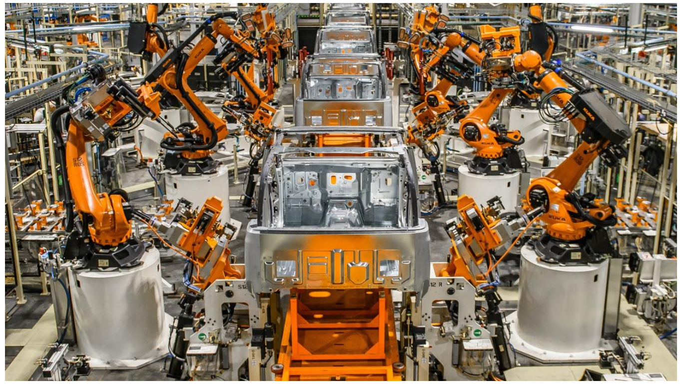
[1]CIRP, “Fundamental terms of manufacturing/grundlegende begriffe der produktion/termini fondamentali della produzione,” in *Dictionary of Production Engineering III – Manufacturing Systems W¨orterbuch der Fertigungstechnik III – Produktionssysteme Dizionario di Ingegneria della Produzione III – Sistemi di produzione: Trilingual Edition Dreisprachige Ausgabe Edizione completa trilingue*, 2020, ch. 1, pp. 1-59.



After 1913, Model T dashboards were assembled on a moving line. Figure credit: Assembly Magazine. https://www.assemblymag.com/articles/91581-the-moving-assembly-line-turns-100



Unimate first applied in GM's plant. Figure credit: The Henry Ford



KUKA Automobile Production. Figure credit: IFR. https://ifr.org/ifr-press-releases/news/one-million-robots-work-in-car-industry-worldwide-new-record

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Ford's moving assembly line

1913

Unimate first applied

1961

Massive robotic assembly line

Since late 20th centuries

Circa 1960

Unimate, Unimation

1974

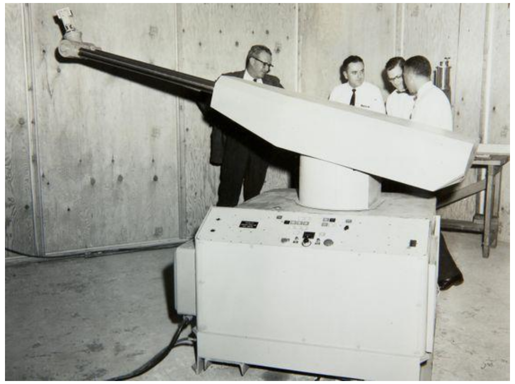
IRB 6, ASEA

2008

UR5, Universal Robot

2015

YuMi, ABB



Unimate from Unimation, the very first industrial robot, circa 1960. Figure Credit: IEEE. https://spectrum.ieee.org/unimation-robot

IRB 6 from ASEA. Figure Credit: ABB. https://new.abb.com/news/detail/106125/140-years-of-asea

YuMi, ABB. Figure Credit: ABB. https://new.abb.com/news/detail/106125/140-years-of-asea

Have we reached the peak of industrial automation?

Assembly in the Automotive Industry

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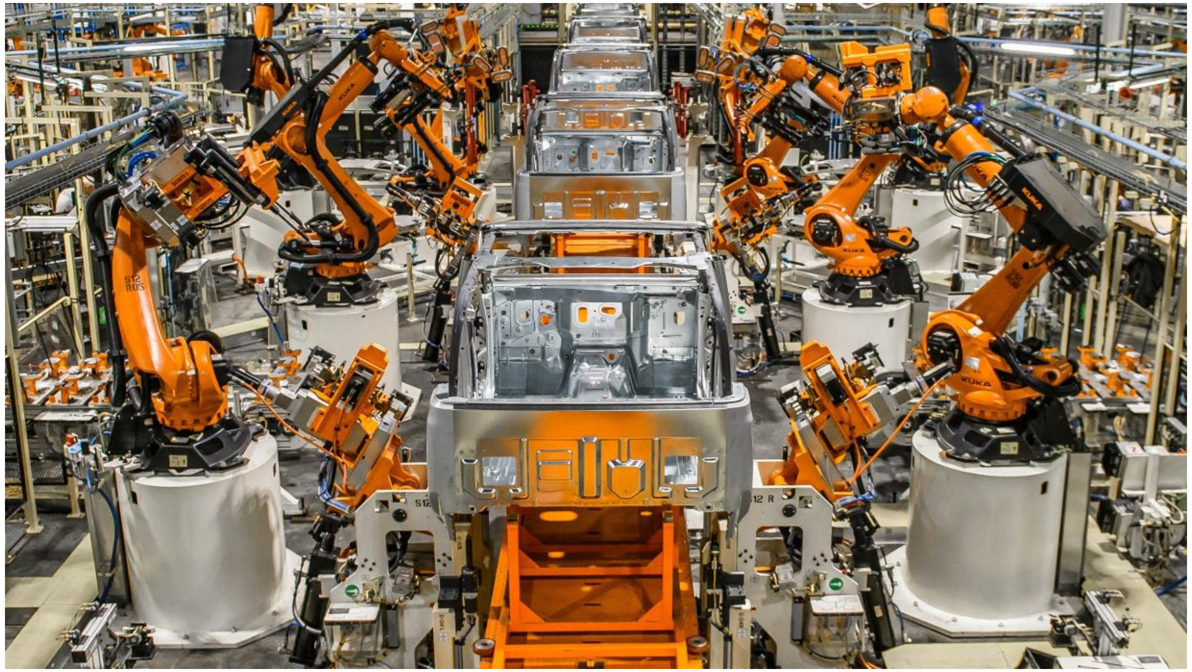
By 2023, about one third of the total number of globally installed robots working in the automotive industry[1].

Body-in-White Assembly



KUKA Automobile Production. Figure credit: IFR. https://ifr.org/ifr-press-releases/news/one-million-robots-work-in-car-industry-worldwide-new-record

Final Assembly

MINI Countryman production at BMW Group Plant Leipzig. Figure Credits: BMW. https://www.press.bmwgroup.com/global/photo/compilation/T0438210EN/one-line-%E2%80%93-two-brands-%E2%80%93-three-drives:-bmw-group-plant-leipzig-launches-production-of-the-mini-countryman

[1]International Federation of Robotics, "One Million Robots Work in Car Industry Worldwide – New Record," 2023. https://ifr.org/ifr-press-releases/news/one-million-robots-work-in-car-industry-worldwide-new-record

Is Industry Not Interested in Scaling up Automation Anymore?

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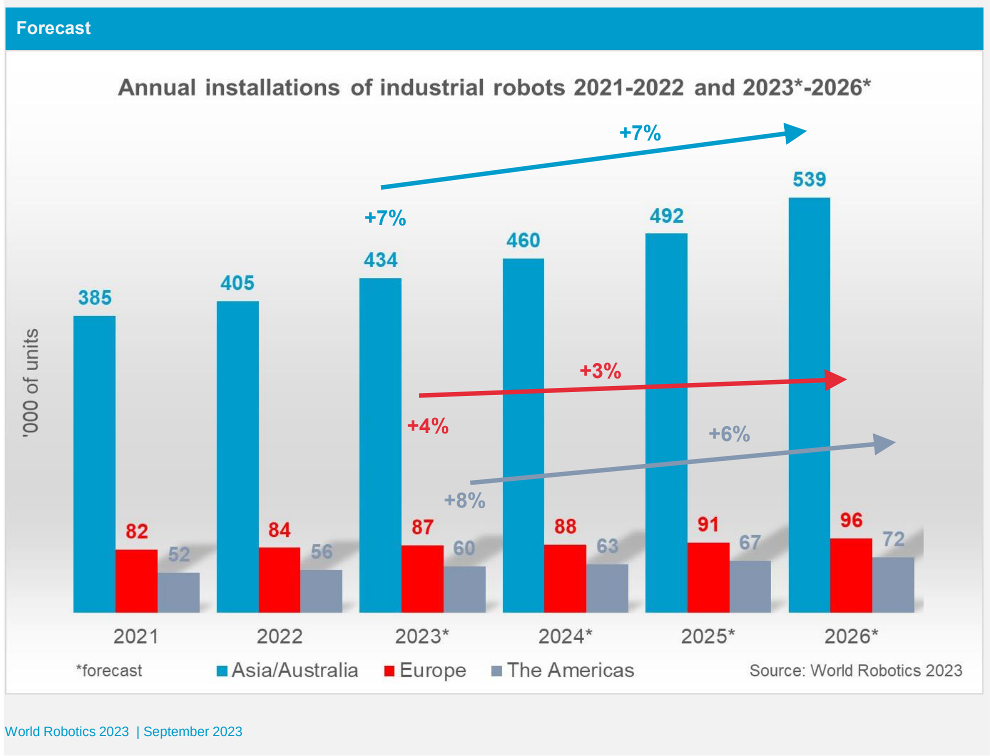
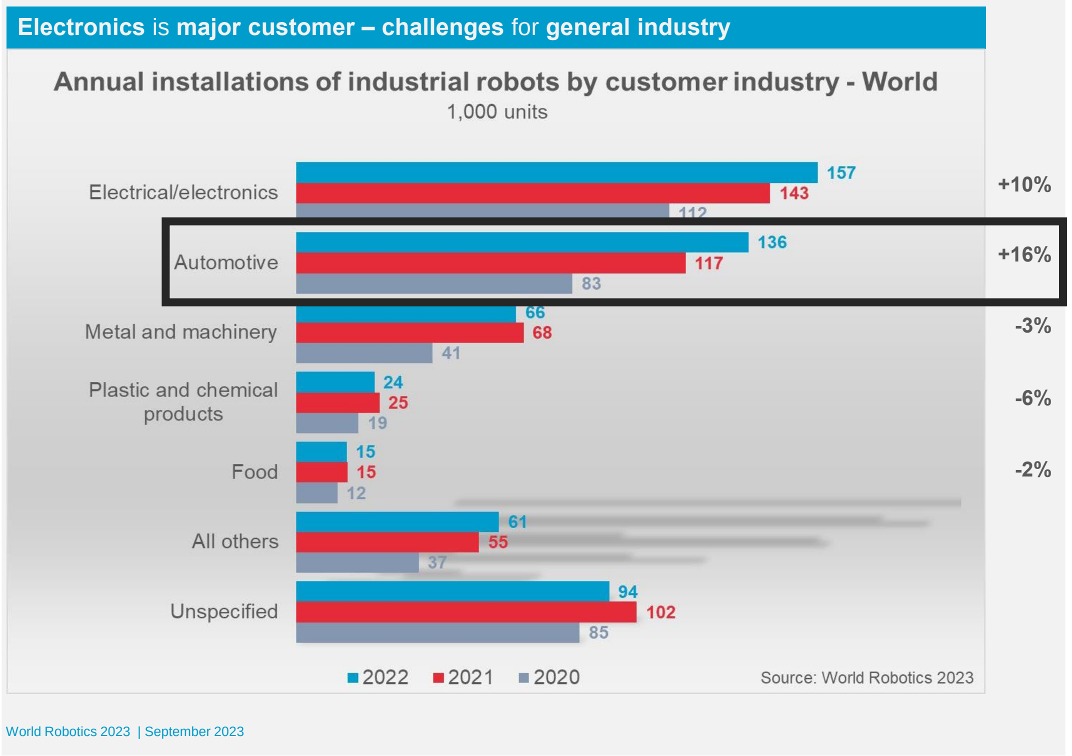


Annual installations of industrial robots 2017-2022 and 2023-2026 by September 2023. Figure Credit: International Federation of Robotics.



Annual installations of industrial robots by customer industry - World September 2023. Figure Credit: International Federation of Robotics.

Market Forecast

- Growing demand

Internal Drivers

- Productivity
- Quality
- …
- Safety
- Ergonomics

External Drivers

- Demographics
- Regulation
- …
- Policy

Is the Technology Ready?

Identifying and Gripping → Transporting → Fitting or Insertion → Securing (optionally)

Sub-procedures consisted in assembly tasks, adapted from T. K. Lien, “Manual assembly,” in *CIRP Encyclopedia of Production Engineering*, 2014, pp. 825–828.

What if impossible to exhaust all scenarios?

Conventional robotic automation

- Robots work repetitively as programmed
- “Identifying” is done by humans
- Humans specify all scenarios ?
- Humans’ intelligence

→

Advanced robotic automation

- Robots work adaptively
- “Identifying” is done by robots
- Robots recognize unseen scenarios
- Robots’ intelligence

Toward Enabling Robotic Visual Perception for Assembly Tasks

An Application in Wire Harness Assembly onto Electric Vehicles

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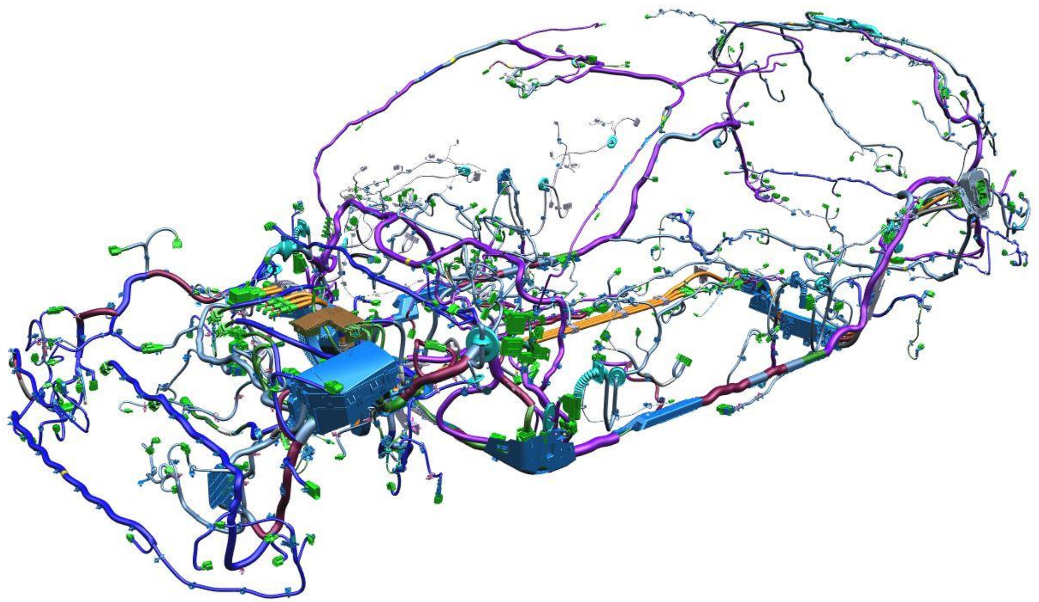
Wire Harnesses

Electrical infrastructure of a passenger car

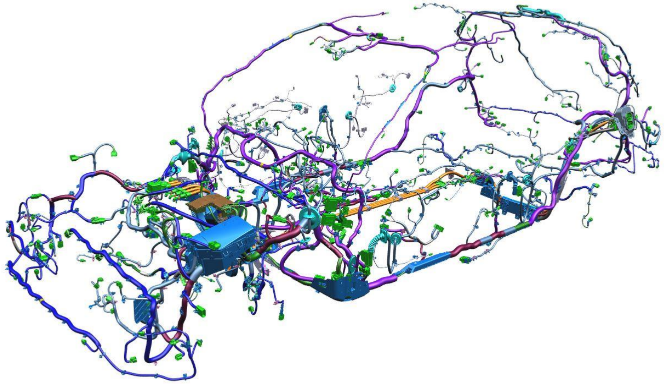


The electrical infrastructure of a Volvo XC 40 Recharge. Figure Credits: Volvo Car Corporation.

Wire harnesses to be assembled in a car

Wire Harness Assembly

Essential Infrastructure



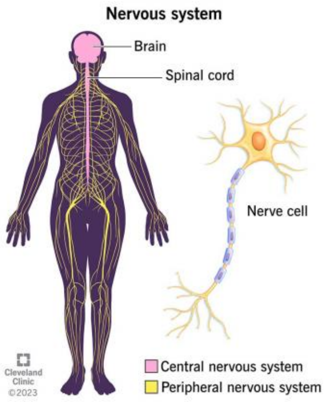
The electrical infrastructure of a Volvo XC 40 Recharge. Figure Credits: Volvo Car Corporation.

Increasing usage of wire harnesses

Year 2000	Year 2003	Year 2008	Year 2020
1000 m	1500 m	2000 m	2800 m

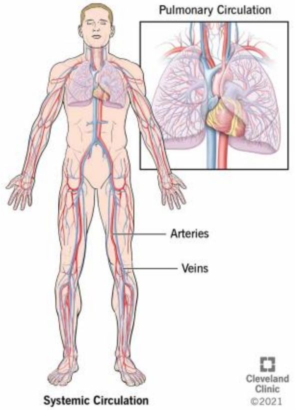
The heavily increasing length of wires in passenger cars over years. Figure Credits: Volvo Car Corporation.

Signal



Nervous system. Figure Credits: Cleveland Clinic. https://my.clevelandclinic.org/health/body/21202-nervous-system

Electric Current



Circulatory System. Figure Credits: Cleveland Clinic. https://my.clevelandclinic.org/health/body/21775-circulatory-system

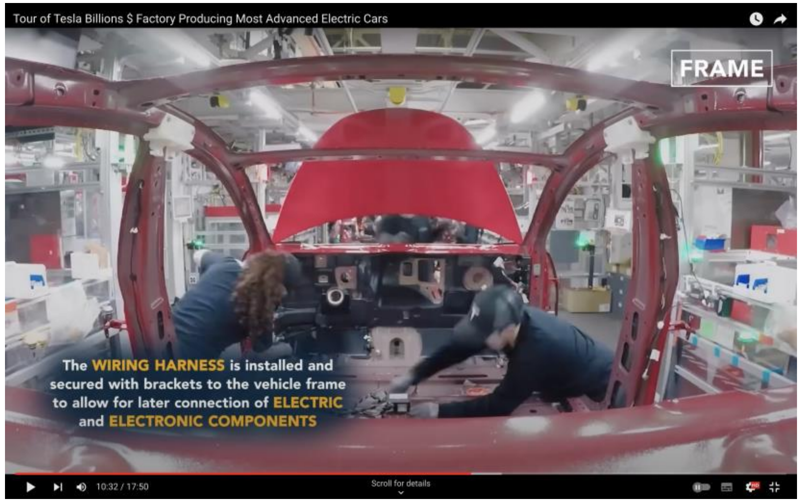
Critical to guarantee

- Quality
- Productivity
- Safety

Wire Harness Assembly

Volkswagen. Video Credits: https://www.youtube.com/watch?v=R2G5SL3Xrdw

Škoda. Video Credits: https://www.youtube.com/watch?v=Tr1B18XJ8Z8



Tesla. Video Credits: https://www.youtube.com/watch?v=QFi6H0qT4j0

Volvo. Video Credits: https://www.youtube.com/watch?v=4T5TKzyv_ds

Current Operations

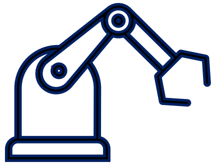
- Repetitive
- Manual
- Skill-demanding

Problems

- Quality
- Productivity
- Safety
- Ergonomics


[1]

Robotic Assembly



[1]G. Michalos, S. Makris, N. Papakostas, D. Mourtzis and G. Chryssolouris, "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.

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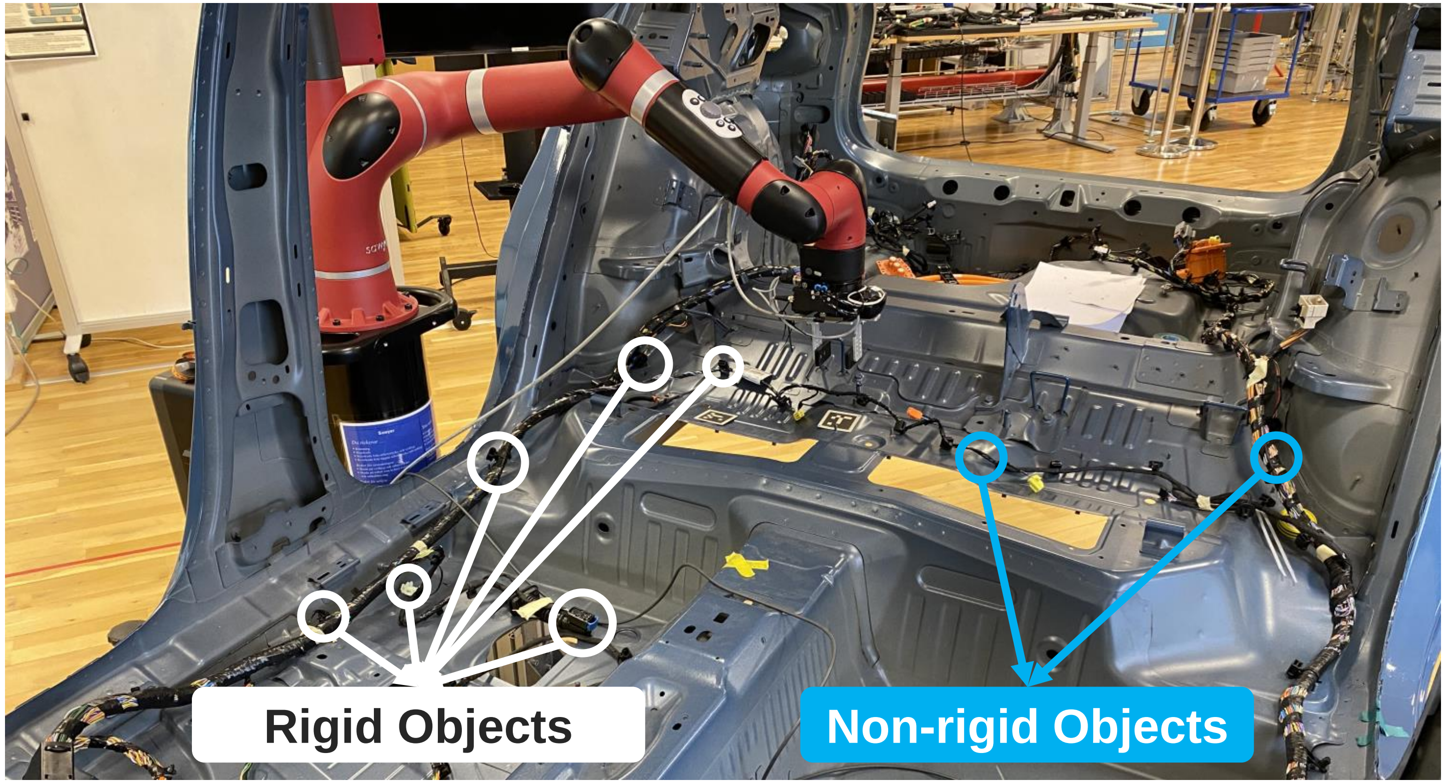
Robotic Assembly - Not There Yet

Unstructured task and environment → Impossible to pre-program[1] → Requiring higher dexterity and adaptability[2]



Identifying and Gripping

↓

Transporting

↓

Fitting or Insertion

↓

Securing (optionally)

Sub-procedures consisted in assembly tasks, adapted from T. K. Lien, “Manual assembly,” in *CIRP Encyclopedia of Production Engineering*, 2014, pp. 825–828.

Robotic Assembly

\+

Visual Input

\+

Perception

[1]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.
[2]G. Michalos, S. Makris, N. Papakostas, D. Mourtzis and G. Chryssolouris, “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.

Vision and Aim

A sustainable manufacturing industry where robots are intelligent and cognizant of their tasks, surrounding environment, and humans nearby

- Robots handle all tasks that are either non-value-adding or not ergonomic to human operators.
- Robots adapt and react flexibly to tasks and situations with minimum human intervention requirements.

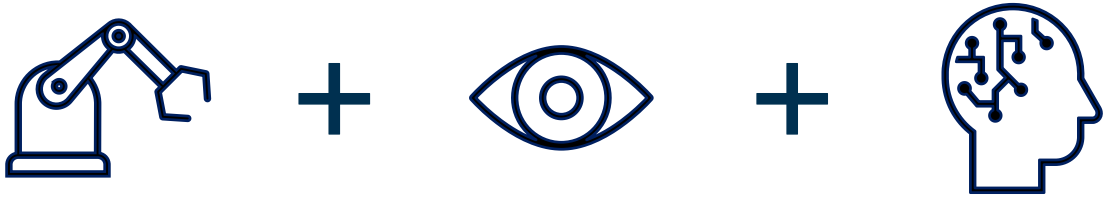
Enable robotic visual perception

Improve the autonomy of industrial robots

Make industrial robots competent in non-predefined tasks

Contribute to the symbiosis of humans and robots

Achieve highly efficient and sustainable production without problems



Robotic Assembly + Visual Input + Perception

Research Questions

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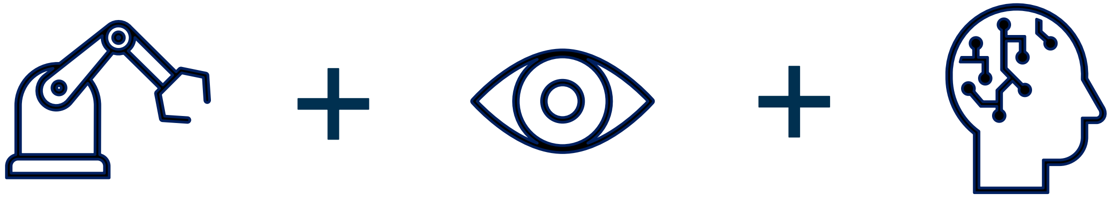
RQ1: What are the challenges of enabling robotic visual perception for assembly tasks?

Guidelines

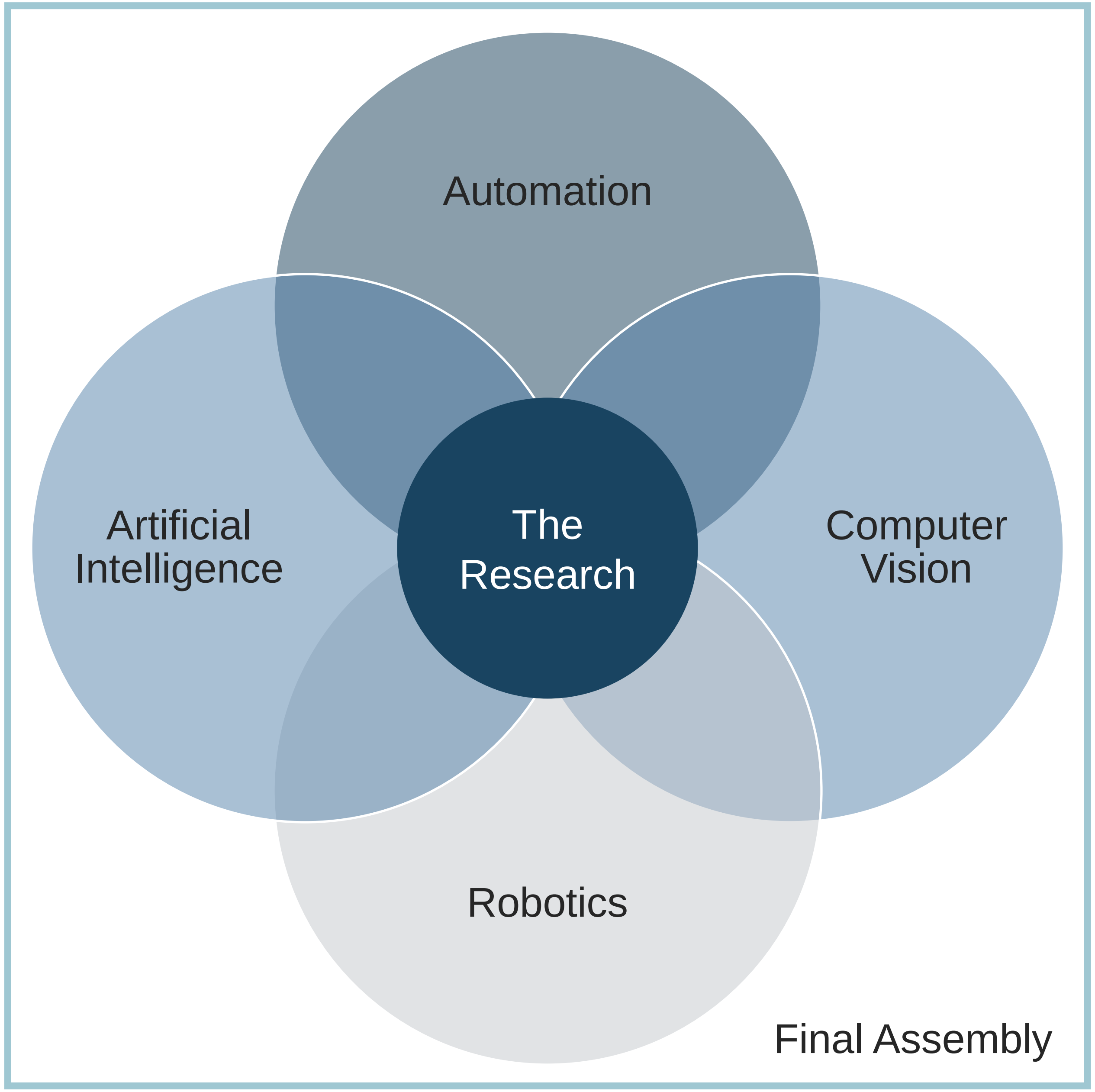
RQ2: How can robotic visual perception be enabled for assembly tasks?

Technical Solutions



Robotic Assembly + Visual Input + Perception

Scope


Automation
Artificial Intelligence
The Research
Computer Vision
Robotics
Final Assembly

Theoretical Framework

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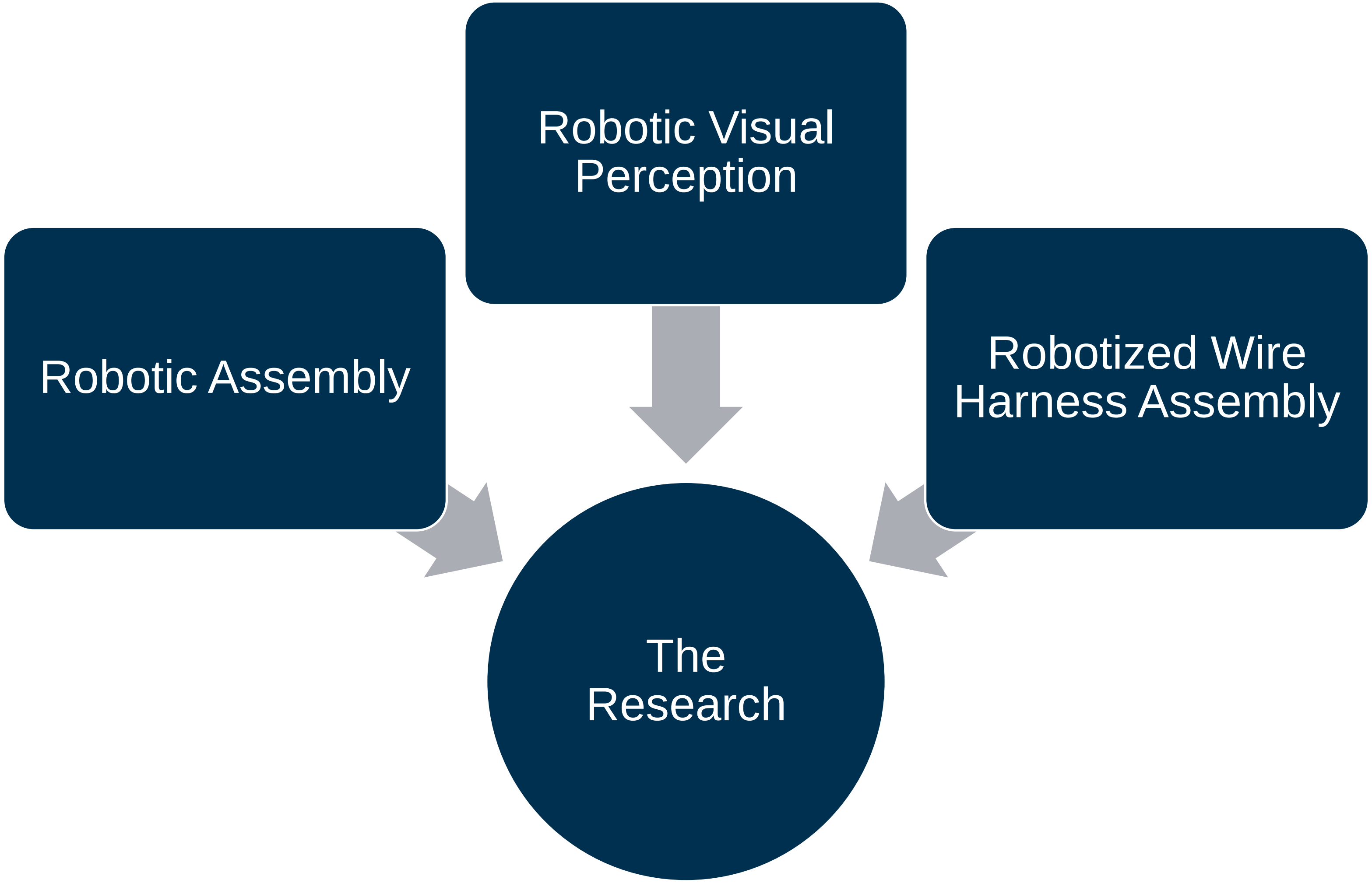
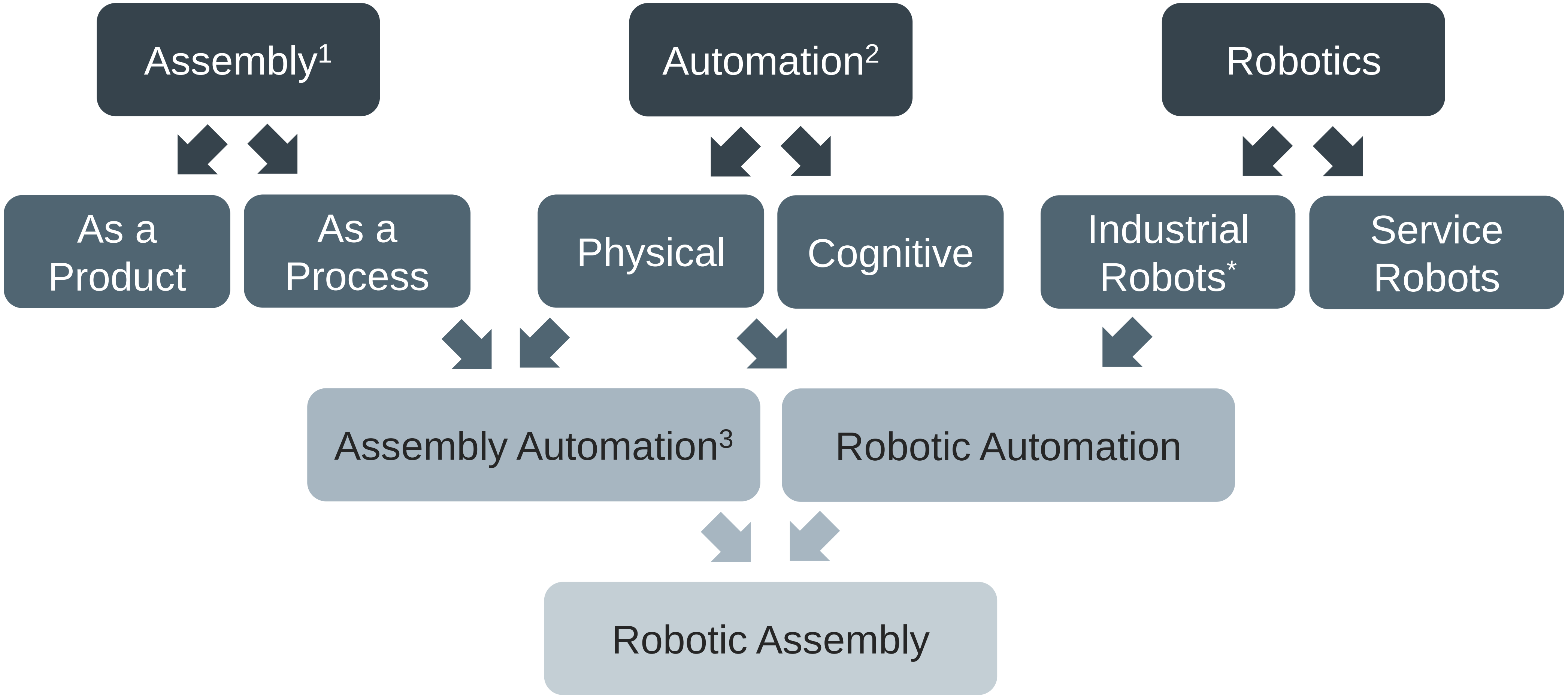
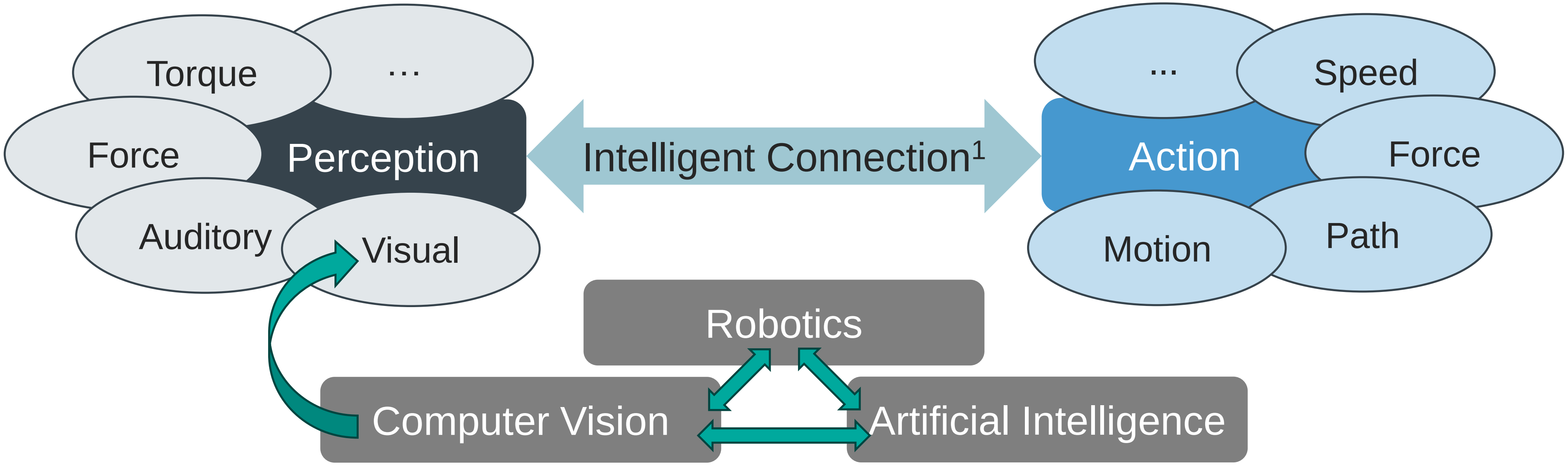


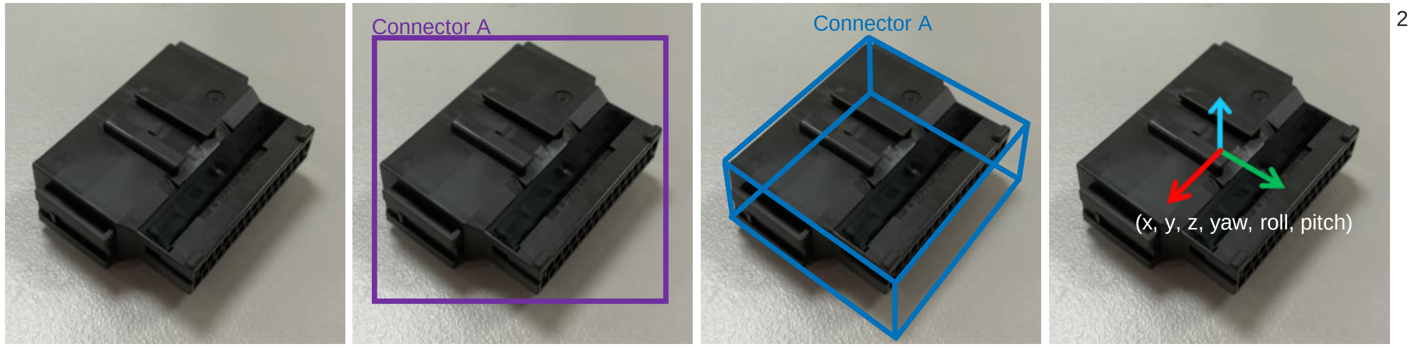
Robotic Assembly



[1] S. J. Hu, “Assembly,” in *CIRP Encyclopedia of Production Engineering*, 2014, pp. 50-52.
[2] Å. Fasth-Berglund and J. Stahre, ‘Cognitive automation strategy for reconfigurable and sustainable assembly systems,’ *Assembly automation*, vol. 33, no. 3, pp. 294-303, 2013.
[3] G. Reinhart, ‘Assembly automation,’ in *CIRP Encyclopedia of Production Engineering*, 2014, pp. 52-54.
*According to ISO 8373:2021 Robotics Vocabulary, a robot is defined as "a programmed actuated mechanism with a degree of autonomy to perform locomotion, manipulation or positioning".

Robotic Visual Perception





Raw Input | 2D Object Detection | 3D Object Detection | 6DoF Object Pose Estimation

[1]M. Brady, "Artificial intelligence and robotics," *Artificial Intelligence*, vol. 26, no. 1, pp. 79-121, 1985.
[2]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.

Robotized Wire Harness Assembly

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Challenges

Wire Harnesses ← Product | Production[1] →

- Effective
- Safe
- Reliable
- Moving
- Robust
- Diverse

Wire Harnesses ⟲ [2] Deformable Linear Objects

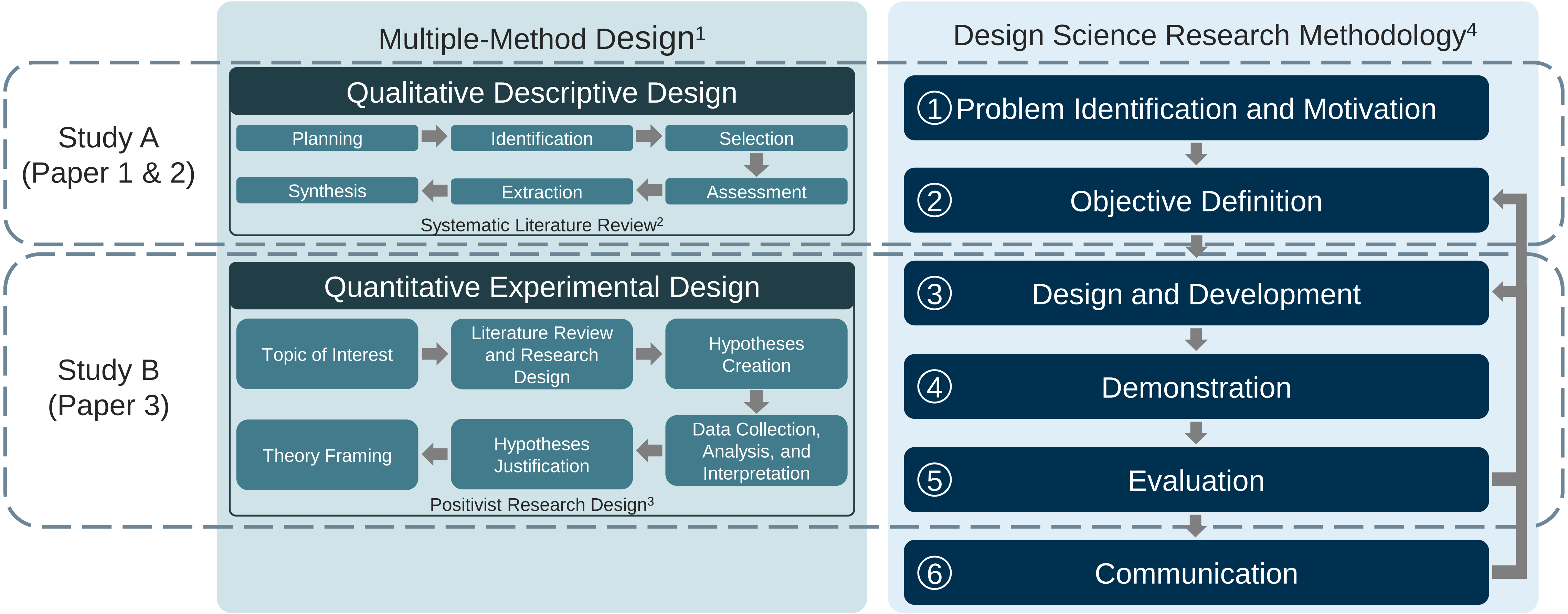
Deformable Linear Objects

Challenges[3]

- Perception
  - **Visual**
  - Sound
  - Force/torque
- Modeling
- Manipulation

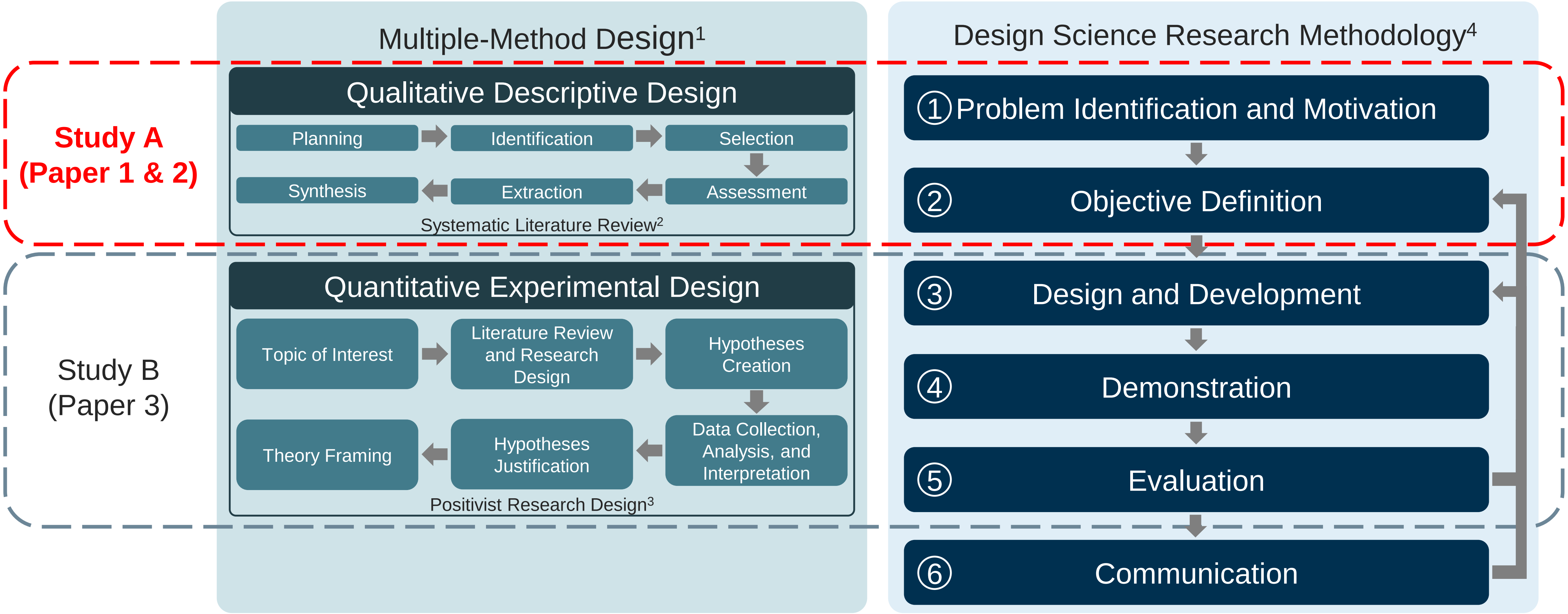
[1]G. Michalos, S. Makris, N. Papakostas, D. Mourtzis and G. Chryssolouris, "Automotive assembly technologies review: Challenges and outlook for a flexible and adaptive approach," *CIRP Journal of Manufacturing Science and Technology*, vol. 2, no. 2, pp. 81-91, 2010.
[2]S. Makris, F. Dietrich, K. Kellens and S. J. Hu, "Automated assembly of non-rigid objects," *CIRP Annals*, vol. 72, no. 2, pp. 513-539, 2023.
[3]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.

Research Design



[1] J. Morse, "Procedures and practice of mixed method design; Maintaining control, rigor, and complexity," in *Sage handbook of mixed methods in social & behavioral research,* pp. 339-352, 2010.
[2] B. Kitchenham, "Procedures for performing systematic reviews," Keele University, Keele, UK, Tech. Rep. TR/SE-0401, 2004.
[3] K. Williamson, F. Burstein and S. McKemmish, "The two major traditions of research," in *Research methods for students, academics and professionals: Information management and systems*, 2nd ed., ch. 2, pp. 25-47, 2002.
[4] 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.

Study A



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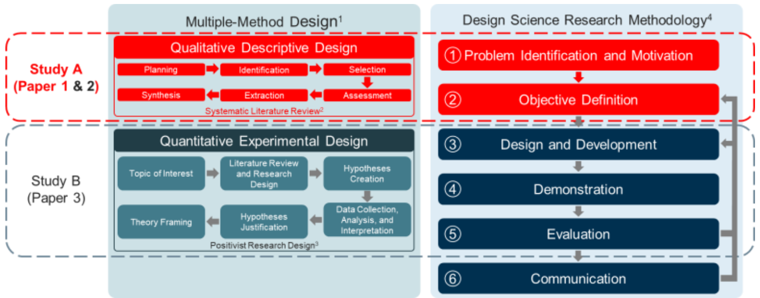

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Paper 1

H. Wang, O. Salunkhe, W. Quadrini, D. Lämkull, F. Ore, B. Johansson and J. Stahre, "Overview of Computer Vision Techniques in Robotized Wire Harness Assembly: Current State and Future Opportunities," *Procedia CIRP*, vol. 120, pp. 1071-1076, 2023, doi: 10.1016/j.procir.2023.09.127.

Overview of Computer Vision Techniques in Robotized Wire Harness Assembly

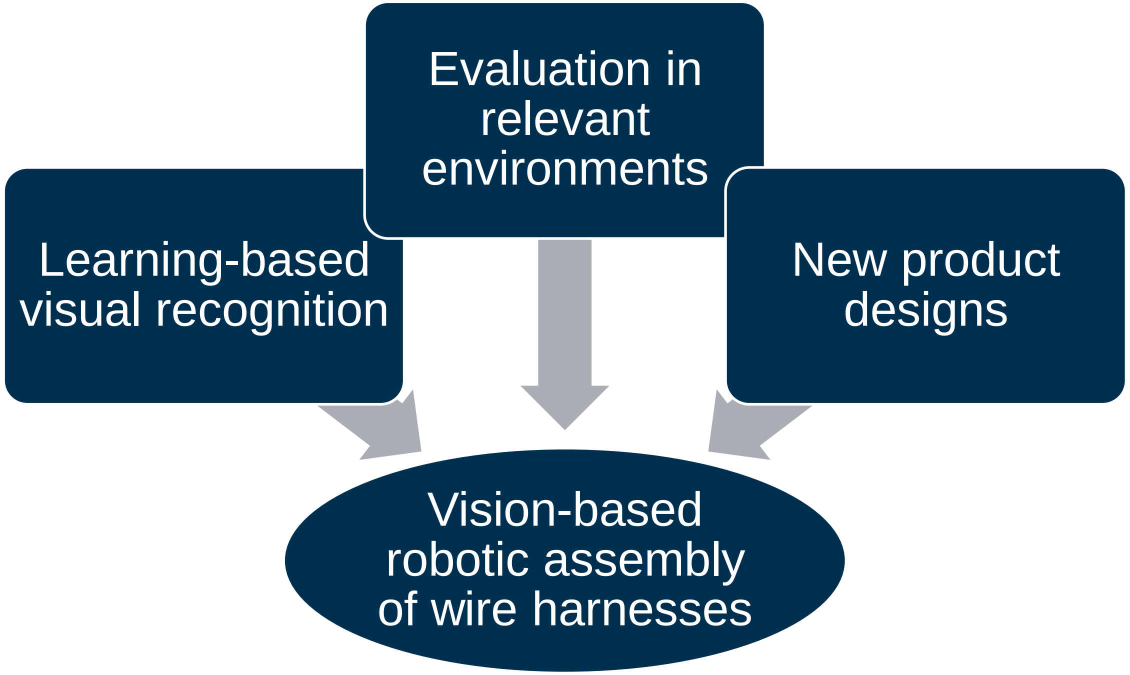
- What is the current state of vision-based robotized wire harness assembly?
- What are the remained tasks for developing vision systems for robotized wire harness assembly?

Literature Search
- Scopus
- (wir* OR cabl*) AND (harness* OR bundl*) AND assembl*

Literature Selection
- Final assembly of wire harnesses onto other products
- Proposing vision systems for the robotized assembly
- Not review and conference review
- English

Component Manipulation
- Clamp insertion
- Connector mating

Structure Perception
- Branch classification
- Cable recognition & segmentation



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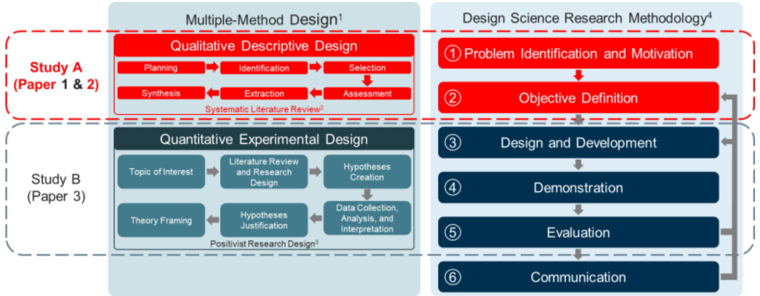

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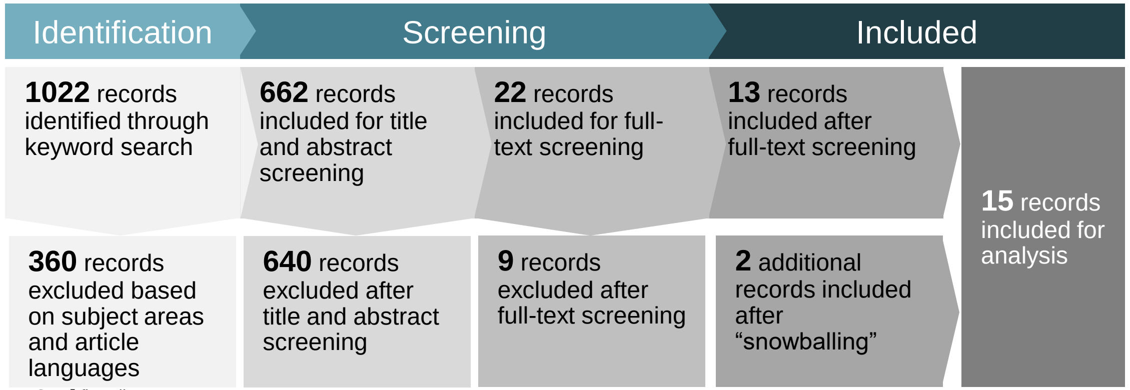
Paper 2

H. Wang, O. Salunkhe, W. Quadrini, D. Lämkull, F. Ore, M. Despeisse, L. Fumagalli, J. Stahre and B. Johansson, "A Systematic Literature Review of Computer Vision Applications in Robotized Wire Harness Assembly," *Accepted for publication in Advanced Engineering Informatics*, May 8, 2024.

A Systematic Literature Review of Computer Vision Applications in Robotized Wire Harness Assembly

- 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?

Database	Scopus
Search string	(wir* OR cabl*) AND (harness* OR bundl*) AND assembl*
Search field	Article title, Abstract, Keywords



PRISMA[5] flow diagram

15 State-of-the-Art Studies

- 4 for clamp manipulation
- 7 for connector mating
- 3 for wire harness recognition
- 1 for wire harness bag segmentation

2 Major Challenges

- Robustness and practicality
- Exploiting intrinsic features

5 Future Research Directions

- Develop learning-based computer vision techniques
- Adapt vision systems proposed for wire harness manufacturing
- Assess vision systems' practicality, robustness, reliability, and sustainability
- Investigate semi-automation with human-robot collaboration
- Explore new product designs for facilitating visual recognition

[1]J. Morse, "Procedures and practice of mixed method design; Maintaining control, rigor, and complexity," in *Sage handbook of mixed methods in social & behavioral research,* pp. 339-352, 2010.
[2]B. Kitchenham, "Procedures for performing systematic reviews," Keele University, Keele, UK, Tech. Rep. TR/SE-0401, 2004.
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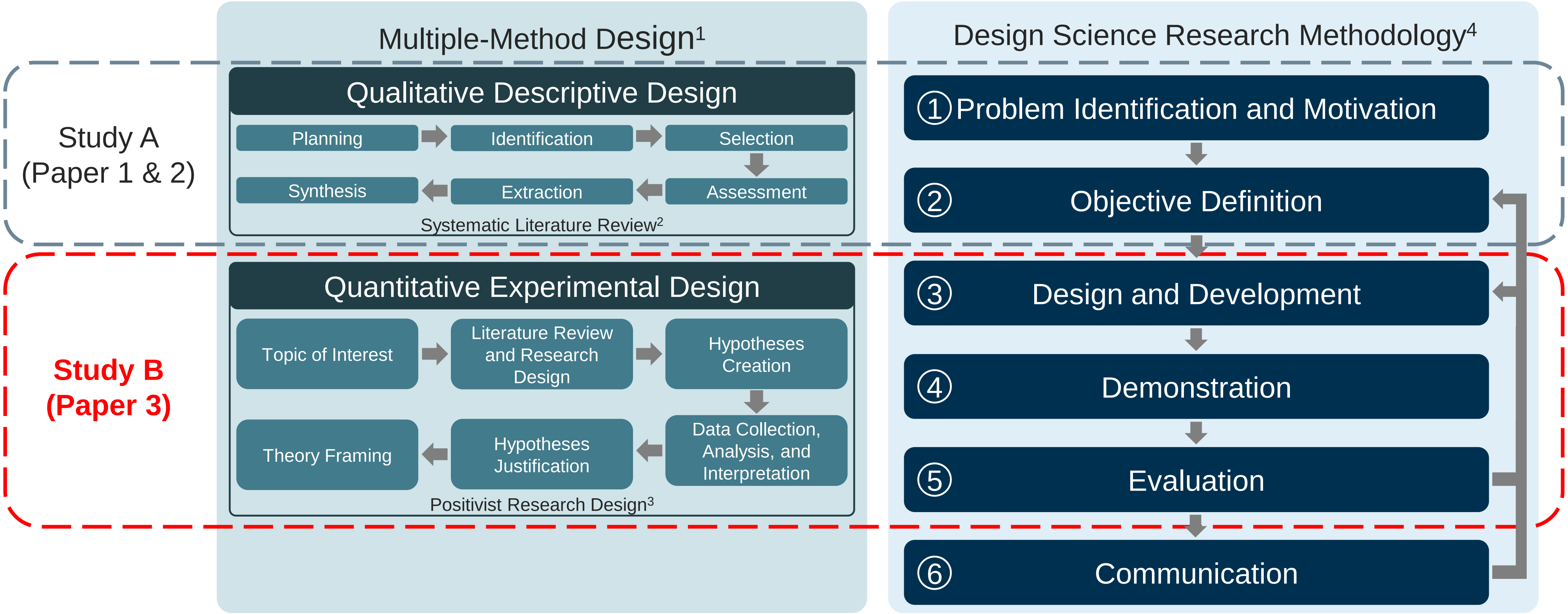
[4]K. Peffers, T. Tuunanen, M. A. Rothenberger and S. Chatterjee, "A design science research methodology for information systems research," *Journal of management information systems*, vol. 24, no. 3, pp. 45-77, 2007.
[5]M. J. Page, J. E. McKenzie, P. M. Bossuyt, I. Boutron, T. C. Hoffmann, C. D. Mulrow, L. Shamseer, J. M. Tetzlaff, E. A. Akl, S. E. Brennan, R. Chou, J. Glanville, J. M. Grimshaw, A. Hróbjartsson, M. M. Lalu, T. Li, E. W. Loder, E. Mayo-Wilson, S. McDonald, L. A. McGuinness, L. A. Stewart, J. Thomas, A. C. Tricco, V. A. Welch, P. Whiting and D. Moher, "The PRISMA 2020 statement: an updated guideline for reporting systematic reviews," *BMJ*, vol. 372, pp. n71, 2021.

Study B



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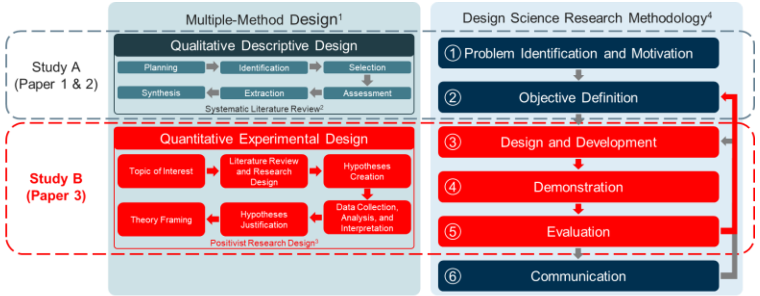
[2] B. Kitchenham, "Procedures for performing systematic reviews," Keele University, Keele, UK, Tech. Rep. TR/SE-0401, 2004.
[3] K. Williamson, F. Burstein and S. McKemmish, "The two major traditions of research," in *Research methods for students, academics and professionals: Information management and systems*, 2nd ed., ch. 2, pp. 25-47, 2002.
[4] 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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Paper 3

H. Wang and B. Johansson, "Deep Learning-Based Connector Detection for Robotized Assembly of Automotive Wire Harnesses," *2023 IEEE 19th International Conference on Automation Science and Engineering (CASE)*, Auckland, New Zealand, 2023, pp. 1-8, doi: 10.1109/CASE56687.2023.10260619.

Deep Learning-Based Multi-class Connector Detection

- Are deep learning-based object detectors effective on connector detection?
- What are the potential obstacles for achieving a practical learning-based connector detection?

Dataset Collection | **Training & Testing** | **Contribution**

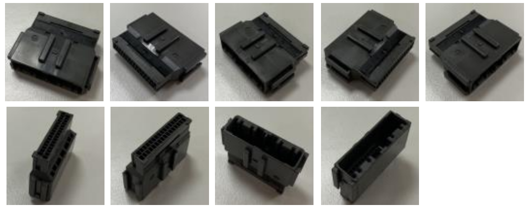
Connector Dataset (360 images)

Mixed-connector images (60 images)

Profile images (6 images/connector)

Front | Left | Top | Back | Right | Bottom

Random-view images (9 images/connector)



Two-Stage Detector
- Faster R-CNN[5]

One-Stage Detector
- YOLOv5[6]

Collected an RGB dataset for 2D connector detection

Verified the effectiveness of deep learning-based connector detection

Identified the insufficient dataset and the current connector designs as hindrances of detection

[1]J. Morse, "Procedures and practice of mixed method design; Maintaining control, rigor, and complexity," in *Sage handbook of mixed methods in social & behavioral research,* pp. 339-352, 2010.
[2]B. Kitchenham, "Procedures for performing systematic reviews," Keele University, Keele, UK, Tech. Rep. TR/SE-0401, 2004.
[3]K. Williamson, F. Burstein and S. McKemmish, "The two major traditions of research," in *Research methods for students, academics and professionals: Information management and systems*, 2nd ed., ch. 2, pp. 25-47, 2002.
[4]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.
[5]S. Ren, K. He, R. Girshick and J. Sun, "Faster r-cnn: Towards real-time object detection with region proposal networks," in *Advances in Neural Information Processing Systems*, vol. 28. Curran Associates, Inc., pp. 91-99, 2015.
[6]G. Jocher, *Yolov5 by Ultralytics*, version 7.0, 2020.

Answers to RQ1

What are the challenges of enabling robotic visual perception for assembly tasks?

- Objects of interest
  - Visual recognition and tracking without being assisted by artificial fiducial markers
  - Obtaining spatial information in 3D space with high precision
  - Challenges due to product design (size, structure, color)
- Application in production
  - Guaranteeing the practicality, reliability, robustness, and sustainability in production

Paper	Contribution to RQ1
1	Minor
2	Major
3	Minor

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Answers to RQ2

How can robotic visual perception be enabled for assembly tasks?

- Adopting learning-based approaches
- Learning from intrinsic features
- Investigating multi-view and/or multi-modality data
- Collecting benchmark datasets for training and evaluating learning-based approaches
- Evaluating vision systems under practical production conditions
- Developing vision-based human-robot collaboration
- Exploring new product designs to facilitate visual recognition

Paper	Contribution to RQ2
1	Major
2	Major
3	Major

Contributions

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To academia

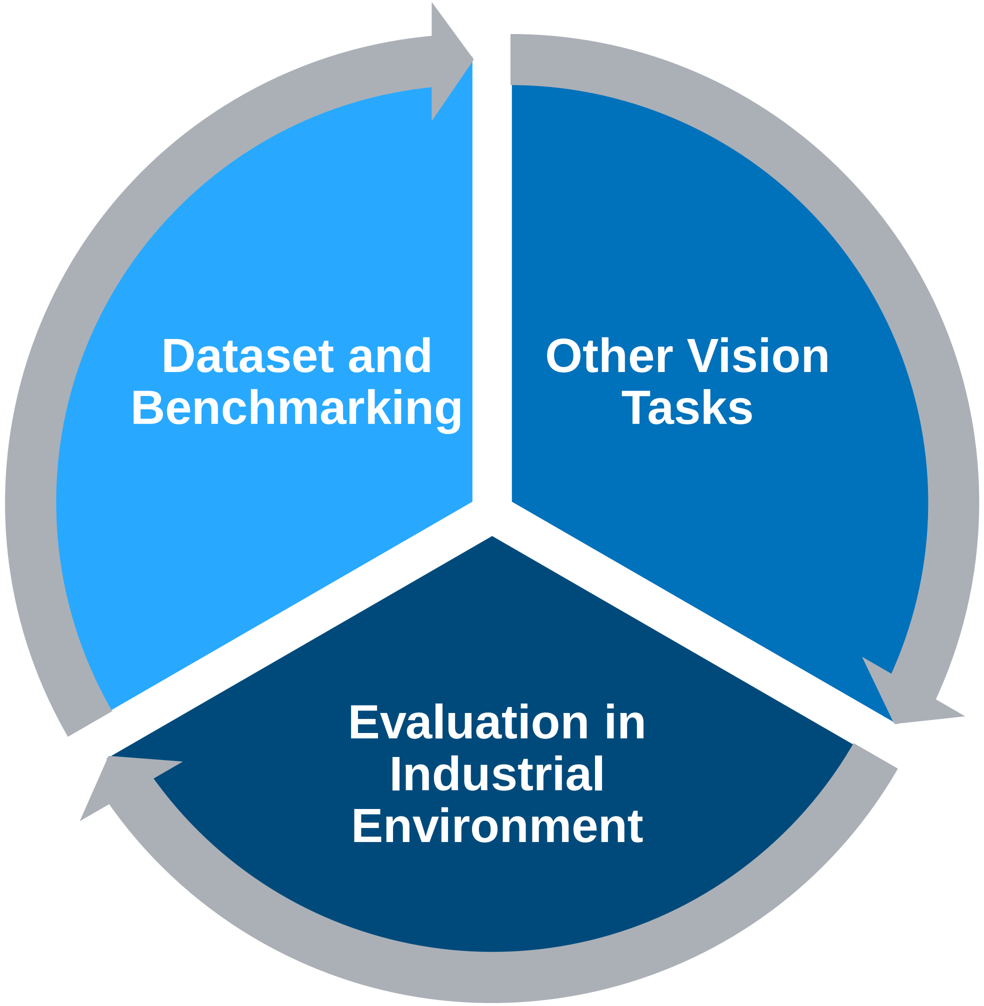
- Identified challenges and future opportunities toward enabling robotic visual perception for assembly tasks
- Verified the effectiveness of deep learning-based vision systems on 2D object detection in robotic assembly tasks

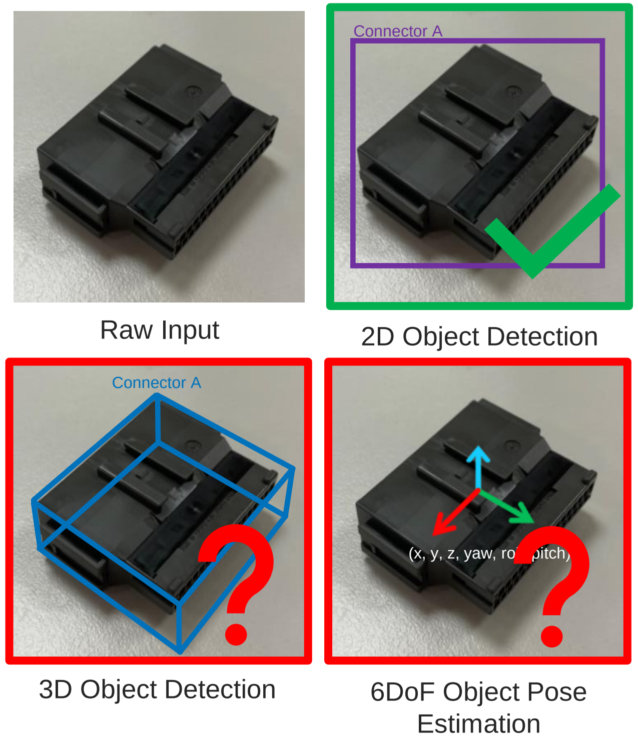
To industry

- Proposed a workflow for developing deep learning-based solutions for 2D object detection in robotic assembly
- Advocated re-considerations on the design of assembly lines and products
- Estimated a promotion of technology readiness level (TRL)[1] from 2-3 to 3-4

[1] J. C. Mankins, "Technology readiness assessments: A retrospective," *Acta Astronautica*, vol. 65, no. 9, pp 1216-1223, 2009.

Future Research





Conclusion

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Challenges

- **Intrinsic feature**-based visual recognition
- **Structure and topology recognition and tracking** for non-rigid objects
- High-precision object **position and orientation acquisition**
- Efficient, effective, and safe **application in production**

Research Needs

- Develop and implement **learning-based computer vision techniques** to exploit intrinsic features of objects
- Exploit **multi-view and/or multi-modality visual inputs** to strengthen the robustness of visual recognition
- Collect **benchmark datasets** for training and evaluating vision systems
- **Evaluate** vision systems **in relevant environments**
- Investigate **new product design** for facilitating visual recognition
- Explore **vision-based human-robot collaboration**

Implications

- Evidence of **challenges and opportunities** for enabling robotic visual perception for assembly tasks
- Foundation of **analyzing and developing** vision systems for specific assembly tasks in production

Thank You!

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