



**Politecnico
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Humanoid Robots in Manufacturing: A Topic Modelling Review of Current Research and Future Perspectives

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1. Introduction

1.1 Background and motivation

In the last years, humanoid robotics has received more attention in both academic and industrial fields. Robots with human-like features are not only research prototypes or entertainment tools anymore. They are now used in areas like manufacturing, logistics, healthcare, and education. The anthropomorphic design and advanced functions make them useful to support complex tasks and to create more natural interaction with people.

At the same time, the fast growth of artificial intelligence and immersive technologies is changing the way humans and machines work together. Because of this, the number of publications on humanoid robotics has increased a lot, but the literature is fragmented into different disciplines and applications. This fragmentation makes it difficult to have a clear and structured overview of the field.

To answer this problem, some studies proposed text mining and topic modelling as systematic methods to analyze large collections of scientific publications (Roberts, M. E., Stewart, B. M., & Tingley, D., 2019). In particular, the study of Barravecchia, Mastrogiacomo, and Franceschini (2021)¹ applied Latent Dirichlet Allocation (LDA) to literature on Product-Service Systems, showing that this approach can highlight research trends and gaps. This methodology is a reference for this thesis.

1.2 The aim of the thesis

The main goal of this thesis is to study the role of humanoid robots in manufacturing and related contexts using two complementary approaches:

¹ (Barravecchia, F., Franceschini, F., Mastrogiacomo, L., 2021)

- A literature review, that explains the main steps in the development of humanoid robots, their technical features, and their applications in industrial scenarios.
- A topic modelling analysis, applied to a corpus of scientific publications from Scopus, to identify the main research themes, their evolution, and their connections.

The idea is to combine a descriptive overview with a quantitative analysis. In this way, it is possible to give a structured understanding of how humanoid robotics evolved, which technologies are most studied, and what directions could appear in the future.

Finally, to connect the theory with something real, the thesis includes a case study about Amazon and the humanoid robot Digit. It's one of the first big projects where a humanoid is tested in real warehouse and factory work. This case is a clear example that humanoid robots are becoming more important for industry and it also confirms what came out from the literature analysis.

1.3 Structure of the thesis

The thesis is divided into six main chapters:

1. Chapter 1 - Introduction: context, objectives, and structure of the work.
2. Chapter 2 – History and evolution of humanoid robots : overview of humanoid robots, from the first developments to the most recent solutions, with focus on applications in manufacturing.
3. Chapter 3 - Methodology and topic modelling: description of the method used, inspired by Barravecchia et al. (2021)², including preprocessing, topic selection, labelling, and validation.
4. Chapter 4 – Topic analysis: topic modelling analysis, showing the summary of each topic, its IMTP charts and temporal trends.

² (Barravecchia, F., Franceschini, F., Mastrogiacomo, L., 2021)

5. Chapter 5 – Case study: Amazon and humanoid robot Digit: analysis of one of the first industrial pilots employing humanoid robots in warehouse and manufacturing operations.
6. Chapter 6 - Conclusions: summary of findings, discussion of limitations, and perspectives for future research and industrial adoption.

2. History and evolution of humanoid robots

2.1 Definition and main characteristics of humanoid robots

A humanoid robot is a robotic system designed to reproduce the morphology of human beings, both in form and in behaviour. It usually consists of a torso, a head, two arms, and two legs, a configuration that makes it suitable for operating in environments and with objects created for humans (Kopacek P., 2012). This anthropomorphic choice is not merely aesthetic: it has clear functional consequences. For example, it allows humanoids to navigate human spaces such as corridors and stairs, to use standard tools, and to communicate with people in a more natural way (Allspaw, J., Heinold, J., & Yanco, H. A., 2019).

From a technical perspective, humanoid robots combine three fundamental components. Sensors provide perception of the environment through cameras, microphones, and tactile systems, enabling a multimodal representation of the context (Allspaw, J., Heinold, J., & Yanco, H. A., 2019). Actuators, such as electric motors and geared mechanisms, are responsible for the movements of limbs and hands. Recent designs have emphasized speed, torque, and the ability to ensure safe physical interaction (Kosanovic N.; Vaz J.C., 2024). Finally, control systems integrate dynamic models and artificial intelligence algorithms to plan complex movements such as bipedal locomotion, manipulation, and balance maintenance (Li F.; Chen C.-H.; Liu Y.; Chang D.; Cui J.; Sourina O., 2024).

One of the most relevant differences from industrial robots lies in their vocation for interaction with humans. While factory robots are optimized for repetitive and high-precision tasks, often confined within enclosed cells, humanoids are developed to communicate and collaborate with people in a natural way, using speech, gestures, physical contact, and even facial expressions. Experiments with robots such as Pepper have shown that the management of dialogue and joint attention fosters a smoother and more accepted relationship with users (Stancioi C.-M.; Fisca M.; Stan O.P.; Misaros M.; Clitan I.; Mihai A.; Muresan V.; Unguresan M.-L., 2021). At the same

time, specific studies have highlighted that the use of humanoids in public contexts also requires cybersecurity assessments, as demonstrated by vulnerability analyses carried out on Pepper (Giaretta A.; De Donno M.; Dragoni N., 2018)

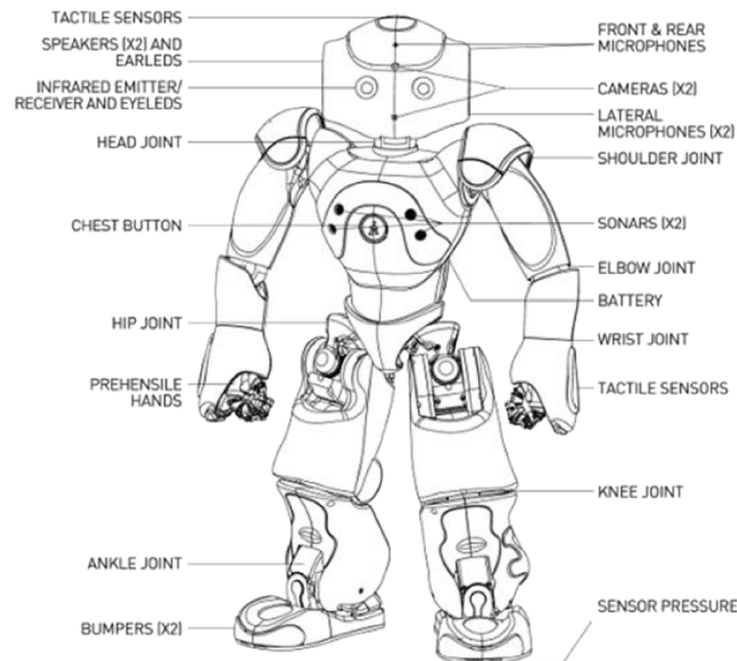


Figure 1: Illustration of the shape and structure of the NAO humanoid robot³

Another important contribution comes from the concept of cost-oriented humanoid robots, which distinguishes low-cost platforms, intended for research and education, from advanced and much more expensive systems designed for high-performance applications. This approach highlights how the evolution of humanoid robots is linked not only to technological advances but also to economic and social factors (Kopacek P., 2012). In this line of research, one study proposed a control architecture specifically tailored for cost-oriented humanoid robots (d'Apolito F.; Mehmeti X.; Kopacek P., 2016). Another work focused instead on the communication architecture, aiming to improve scalability and ease of use (Dincer F.; Byagowi A.; Kopacek P., 2019).

Finally, particular attention has been devoted to the development of anthropomorphic robotic hands, which decisively affect the effectiveness of humanoid robots. Dexterity in grasping and the ability to manipulate objects depend on the design of fingers and

³ (Hu, Sirlantzis, Howells, & Rodriguez, 2016)

palm, the compliance of materials, and the level of control achieved (Apriandy K.I.; Ulurrasyadi F.; Dewanto R.S.; Dewantara B.S.B.; Pramadihanto D., 2024). Another study has introduced an ambidextrous human-like robotic hand to enhance manipulation skills in complex scenarios (Hamouda A.M.; Abdellatif E.M.; Al Akkad M.A., 2024).

To better illustrate the differences, the following *Table 1* compares the main features of industrial robots and humanoid robots:

Aspect	Industrial robots	Humanoid robots
Form	Arms or axes on a fixed structure	Anthropomorphic structure (head, torso, arms, legs)
Objective	Repetition and precision in specific tasks	Adaptability, interaction, and collaboration
Operating environment	Highly structured production lines	Human environments (homes, offices, hybrid factories)
Interaction	Pre-programmed, isolated by safety barriers	Speech, gestures, physical contact, natural language
Flexibility	Low, difficult to reprogram	High, with learning and fast reconfiguration
Examples	ABB, FANUC, KUKA	WABOT-2, NAO, Pepper

*Table 1: Comparison between industrial and humanoid robots.*⁴



Figure 3: ABB - Industrial robot (Exapro, s.d.)



Figure 2: NAO - Humanoid robot (SoftBank Robotics, s.d.)

⁴ Note: Table created by the author based on data from Kopacek (2012), Allspaw et al. (2019), and Stancioi et al. (2021).

In summary, humanoid robots are defined by the combination of an anthropomorphic form, advanced sensory and actuation capabilities, and above all an orientation toward natural interaction with humans. These elements make them a distinct category compared to industrial robots and lay the foundation for understanding their evolution and future prospects.

2.2 Historical evolution of humanoid robots

The development of humanoid robots follows some technological waves: from the first academic demonstrations to stable locomotion, until agile platforms ready for real scenarios. The anthropomorphic design was made to work in spaces created for humans and to interact in a natural way with people (Kusuda, 2002).

In the 1970s, Waseda University started the WABOT project with the goal to create a “personal” robot with perception, locomotion, and communication (University Waseda, n.d.). The result was **WABOT-1** (1973), considered the first full-size humanoid with limbs, vision, and dialogue in Japanese (University Waseda, n.d.)

In the next decade, **WABOT-2** (1980–1984) was created, designed to play keyboard instruments: the system could read scores, follow a singer, and accompany him, integrating vision, hearing, and fine manipulation (Sugano, S., Tanaka, Y., Ohoka, T., & Kato, I., 1985). A later summary explained its motor, visual, and vocal subsystems and the evolution towards public demonstrations (Kato, 1987)

Between the 1990s and early 2000s, research focused on whole-body control and imitation from demonstration. Dariush et al.⁵ showed how the use of human motion descriptors allowed to reproduce coordinated postures and gestures. Later, Mühlig et al.⁶ improved this approach with imitation and optimization techniques, showing that complex tasks could be learned and repeated in a more robust way.

⁵ (Dariush, B., Gienger, M., Jian, B., Goerick, C., & Felis, M., 2008)

⁶ (Mühlig, M., Gienger, M., Hellbach, S., Steil, J. J., & Goerick, C., 2009)

With the **ASIMO** era, the focus moved to stable walking and integration of control and interaction subsystems. A unique interface for arms, base, and “androids” showed how to coordinate degrees of freedom for demonstrative tasks and dialogue. ASIMO soon became a world icon thanks to its ability to walk, run, climb stairs, and carry small objects. (Yang, A. Y., Gonzalez-Banos, H., Ng-Thow-Hing, V., & Davis, J, 2005)

While Honda was working on ASIMO, Japan also launched the Humanoid Robotics Project (HRP), led by AIST and Kawada Industries with support from METI. The first version, **HRP-1** (1998), was based on the Honda P3. It was mainly used as a research platform to study whole-body control and biped walking (Wikipedia, s.d.)

A few years later, **HRP-2 Promet** came out (2002–2003). It was about 1.54 meters tall, weighed 58 kilos, and had 30 degrees of freedom. It ran on 48 V NiMH batteries. Compared to ASIMO, HRP-2 had some clever design changes, like a cantilever hip joint and a waist with two degrees of freedom. Thanks to this, it could get up by itself after falling, either on its back or on its chest (Kaneko et al., 2002)⁷. HRP-2 was not created to be sold as a product. It was mainly built as a research platform, so universities and labs could use it for experiments. Many tests focused on cooperation between humans and robots, for example lifting panels or heavy objects together (Kaneko et al., 2002)⁸. Thanks to these studies, HRP-2 became an important reference in humanoid robotics, especially for industrial and manufacturing use. It also inspired the next versions (HRP-3, HRP-4, HRP-5P) and, compared to ASIMO, it was seen as more practical for real applications.

In the 2010s, “standard” platforms for research and teaching spread. **NAO** (2010, Aldebaran/SoftBank) became a testbed for perception and grasp planning on common objects (Müller, J., Frese, U., & Röfer, T., 2012). At the same time, **Pepper** (2014, Aldebaran then SoftBank) was designed as a social robot able to read human emotions through face recognition and voice tone. Used in shops, airports, and hospitals, it

⁷ (Kaneko, K., Kanehiro, F., Kajita, S., Hirukawa, H., Kawasaki, T., Hirata, M., Shizuma, K., Ishikawa, M., Koyachi, N., & Furusho, J., 2002)

⁸ (Kaneko, K., Kanehiro, F., Kajita, S., Hirukawa, H., Kawasaki, T., Hirata, M., Shizuma, K., Ishikawa, M., Koyachi, N., & Furusho, J., 2002)

showed new possibilities of natural HRI, but also cybersecurity vulnerabilities documented systematically (Giaretta A.; De Donno M.; Dragoni N., 2018).

In the same period, agility and dynamic locomotion became very important. **Atlas** (2013, Boston Dynamics) became a reference for running, jumping, and parkour demonstrations. Its performance did not start from zero, but from a strong research tradition: Dariush, B., Gienger, M., Jian, B., Goerick, C., & Felis, M, (2008)⁹ already showed the importance of whole-body control to reproduce coordinated movements. Later, Mühlig, Gienger, Hellbach, Steil, and Goerick (2009)¹⁰ demonstrated how imitation from demonstration made robots able to learn and repeat complex tasks. In parallel, Ruspini and Khatib (2001)¹¹ created the base for physical contact and haptic interaction, today essential skills to deal with irregular and collaborative scenarios.

From 2020, platforms for industrial and logistic applications appeared. **Digit** (2018, Agility Robotics) was developed for package handling and repetitive tasks in the supply chain, with first uses in real contexts (Agility Robotics, n.d.). At the same time, **Apollo** (2023, Apptronik) was presented as a general-purpose humanoid with focus on productivity, safety, and scalability of production (Apptronik, n.d.). **Ameca** (2021, Engineered Arts), expressive HRI, introduced facial expressions and upper-body movements, becoming a reference for more natural social interactions (Engineered Arts, n.d.)

Also, big automotive players invested in general-purpose humanoids. **Optimus** (2022, Tesla) was announced as a bipedal platform for “dangerous, repetitive, or boring” tasks, with special actuators, advanced hands, and public demos of its newer generations (Tesla, n.d.)

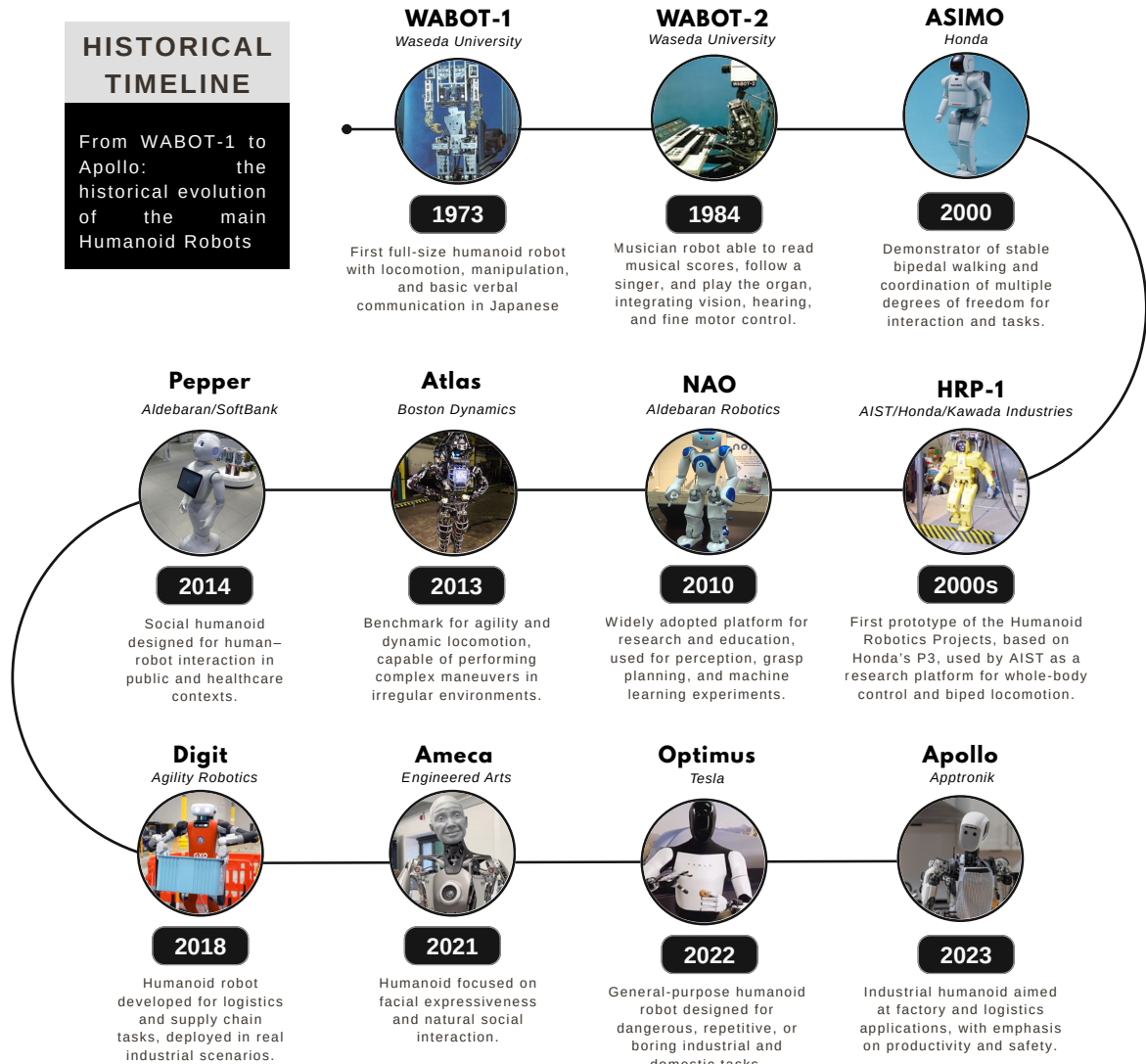
In conclusion, the historical trajectory shows the passage from very specific academic demonstrators, like WABOT-2, to integrated platforms that combine dynamic locomotion, robust perception, and natural interaction. Today the first real applications are in manufacturing, in logistics and services, showing an evolution that transformed

⁹ (Dariush, B., Gienger, M., Jian, B., Goerick, C., & Felis, M, 2008)

¹⁰ (Mühlig, M., Gienger, M., Hellbach, S., Steil, J. J., & Goerick, C., 2009)

¹¹ (Ruspini, D. C., & Khatib, O., 2001)

humanoid robots from experimental prototypes to tools much closer to real scenarios (Kusuda, 2002).



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Figure 4: Historical Evolution of the main Humanoid Robots

2.3 Overview of humanoid robot models available today

The current landscape of humanoid robotics shows many platforms with different goals: from education and research to social interaction, up to robots made for logistics

¹² Note: Figure 2 created by the author.

and manufacturing. Below the main models are presented, with a comparison of technical features, AI integration and adoption status.

NAO (Aldebaran/SoftBank) – Education and Research platform

- Purpose: academic research, teaching robotics and assisted therapy.
- Hardware: 58 cm, 5.5 kg, 25 degrees of freedom (DoF); with cameras, IMU, sonar, microphones and tactile sensors.
- AI: supports basic voice and vision recognition; can be connected with external libraries via SDK (NAOqi).
- Adoptions: used in thousands of schools and labs around the world; also used in clinical projects, for example in therapy with autistic children (Müller, J., Frese, U., & Röfer, T., 2012).



(SoftBank Robotics, s.d.)

Figure 5: NAO Robot

Pepper (Aldebaran → SoftBank) – Social robot

- Purpose: interaction with clients and visitors, front-office tasks.
- Hardware: about 120 cm, ~29 kg, mobile base, 20 motors; integrated chest tablet.
- AI: face and emotion recognition, multimodal dialogue; cloud integration possible.
- Adoptions: used by Nestlé for promotion in Japan and by banks like Mizuho Bank for concierge services; later studies also analyzed its security vulnerabilities (Giaretta A.; De Donno M.; Dragoni N., 2018)



(IEEE SPECTRUM, s.d.)

Figure 6: Pepper Robot

Ameca (Engineered Arts) – Expressive interaction

- Purpose: HRI research and public demonstrations, with focus on natural communication.
- Hardware: 61 degrees of freedom, with 27 in the face; ~187 cm, ~49kg, 51 DoF; cameras, microphones and actuators for smooth and expressive movements.
- AI: Tritium software platform can be connected with vision and language models; optimized for expressive realism.
AI partner: OpenAI.
- Adoptions: shown in fairs and museums; used as attraction and for studies about social acceptance of robots (Engineered Arts, n.d.)



*(AD Middle East Magazine, s.d.)
Figure 7: Ameca Robot*

HRP-5P - Agility Demonstrator

- Purpose: Heavy labor, industrial/construction tasks
- Hardware: 182 cm, 101 kg, 37 DoF
- AI & Autonomy: Perception, object recognition, whole-body motion planning, autonomous execution



- Adoptions: AIST research projects, academic–industrial collaboration (no commercial roll-out) (AIST, 2018), (RobotsGuide).

Figure 8: HRP-5 Robot (Guide, s.d.)

Atlas (Boston Dynamics) – Agility demonstrator

- Purpose: advanced research on dynamic locomotion, agility and manipulation.
- Hardware: bipedal platform with electric actuation (2024 version); able to run, jump and do complex manoeuvres. About 150 cm, 89 kg and 28 DoF.
- AI: control policies and learning based on vision and IMU; recent integration of behaviour models for complex tasks.
AI partner: NVIDIA (Rauf, 2025).

- Adoptions: used only as R&D demonstrator; not commercialized. Test phases within Toyota. Its skills come from early studies on whole-body control (Dariush, B.,

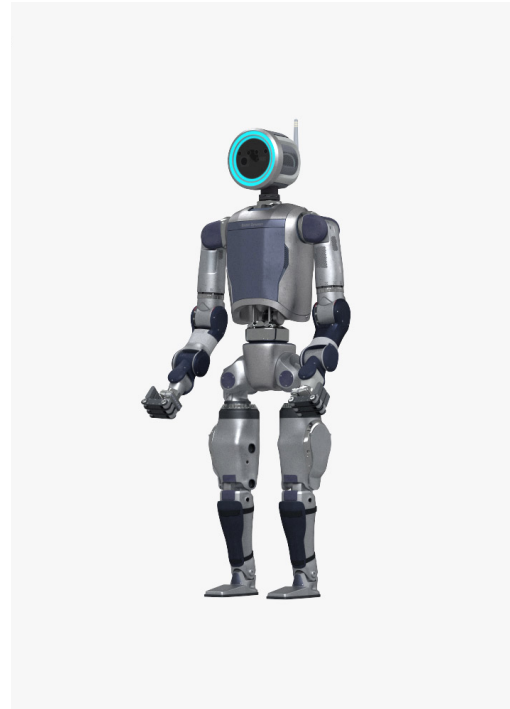


Figure 9: Atlas Robot (3Dmodels, s.d.)

(Gienger, M., Jian, B., Goerick, C., & Felis, M, 2008) imitation (Mühlig, M., Gienger, M., Hellbach, S., Steil, J. J., & Goerick, C., 2009) and physical interaction (Ruspini, D. C., & Khatib, O., 2001)

Digit (Agility Robotics) – logistics

- Purpose: package and material handling in warehouses.
- Hardware: about 175 cm; payload ~16 kg; modular arms; design optimized for standard totes.
- AI: integrated planning and perception for repetitive tasks; fleet coordination with Agility Arc cloud platform.
AI partner: NVIDIA (Rauf, 2025).
- Adoptions: pilot programs with Amazon and GXO; start of large-scale production in Oregon (Agility Robotics, n.d.)



*Figure 10: Digit Robot
(Food Logistics, s.d.)*

Apollo (Appttronik) – industrial general-purpose

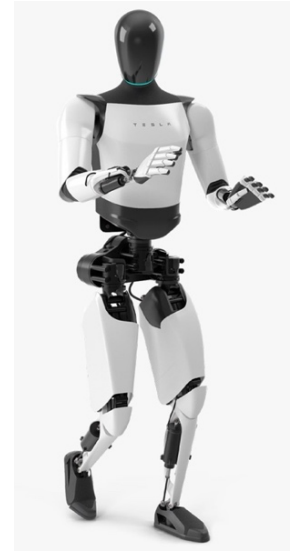
- Purpose: support workers in repetitive and heavy factory tasks.
- Hardware: 175 cm, ~72 kg, payload 25 kg, battery runtime about 4 hours.
- AI: teleoperated mode for training and learning.
force control to work safely near humans.
AI partner: NVIDIA (Rauf, 2025).
- Adoptions: pilot program with Mercedes-Benz in production plants; preliminary agreements with logistic operators (Appttronik, n.d.)



*Figure 11: Apollo Robot
(Appttronik, s.d.)*

Optimus (Tesla) – general-purpose (in development)

- Purpose: robot for “dangerous, repetitive or boring” tasks, with focus on internal logistics and manufacturing.
- Hardware: specifications are evolving but it would be ~175 cm, weight between 57 kg and 73 kg, ~28 DoF in the body and 11 DoF in the hand; the battery should last as long as a ‘working day’.
- AI: integrated with Tesla AI stack (vision and planning).
- Adoptions: for now, only internal use at Tesla, no third-party distribution (Tesla, n.d.)



*Figure 12: Optimus Robot
(Shutterstock, s.d.)*

Other significant examples and emerging trends

- **RoboThespian (Engineered Arts, 2006)** - first commercial humanoid made for museums and science centres. Programmable to act, sing and interact with public; still a reference for edutainment (Engineer Arts, n.d.)
- **Kodomoroid (ATR/Osaka University)** - It has the form of a robot child, and it can read news and interact with visitors. Its realistic design - silicone skin and artificial muscles - makes it an emblematic example of android as art and public communication (Dearden, 2024).
- **Figure 02 (Figure AI, 2024)** - humanoid tested in BMW’s Spartanburg assembly line, capable of autonomous insertion tasks in car frames, developed with AI support from Microsoft, OpenAI and Nvidia (Industria Italiana, 2024)
- **Neo (1X, 2023)** - emerging prototype for home and service market. Supported by investments from OpenAI and Nvidia, it is a recent attempt to connect advanced AI with humanoid platforms (1X Technologies, n.d.)

- **Walker S1 (Ubtech Robotics, 2024)** - deployed in production plants of Byd, Geely, Nio and Volvo; features semantic navigation, tactile sensors and whole-body control for flexible industrial applications (Industria Italiana, 2024).
- **RoBee (Oversonic, 2025)** - Italian humanoid already operating in multiple factories, performing quality control, pick-and-place, and machine tending tasks. About 60 units are active, making it one of the few humanoids in stable industrial deployment (Industria Italiana, 2024).

As underlined by (Transmitter, 2024), the variety of these examples shows that humanoid robots are no longer limited to academic research, but are spreading in industrial, logistic, social and cultural contexts.

Comparative table:

Robot	Main purpose	Hardware	AI & Autonomy	Known adoptions	Current status
NAO	Research, education, therapy	58 cm, 25 DoF, sensors	Basic vision/voice, open SDK	Schools, universities, clinics	Commercial
Pepper	Social interaction	120 cm, mobile base, tablet, 20 motors	Emotion, face/voice recognition, cloud integration	Retail (Nestlé), banks (Mizuho)	Commercial
Ameca	Expressive HRI	187 cm, 49 kg, 51 DoF (27 facial)	External AI models, Tritium platform	Museums, fairs, demos	Commercial
Atlas	Agility, research	~150 cm, 89 kg, 28 DoF, electric actuation	Whole-body control, reinforcement learning, machine learning	Internal R&D (Boston Dynamics)	Demonstrator
HRP-5P	Heavy labor, industrial / construction	182 cm, 101 kg, 37 DoF	Perception, object recognition, whole-body motion planning, autonomous execution	AIST research projects, academic-industrial collaboration	Research prototype / demonstrator
Digit	Logistics	175 cm, payload 16 kg	Perception/planning, cloud fleet	Pilots with Amazon and GXO	Pilot / early production
Apollo	Manufacturing, logistics	175 cm, 72 kg, payload 25 kg, ~4h battery	Teleop-to-autonomy, force control	Pilot with Mercedes-Benz, logistic operators	Pilot
Optimus	Industrial general-purpose	~175 cm, 57–73 kg, ~28 DoF body + 11 hand	Tesla AI stack (vision, planning)	Internal Tesla use	Prototype
RoboThesplan	Edutainment	~175 cm, active torso	Preprogrammed scripts	Museums and science centers	Commercial
Kodomoroid	Exhibition android	Human size, realistic android look	Communication, TV presenter	Miraikan museum, cultural attractions	Demonstrator
Neo (1X)	Service / domestic	~170 cm	Integrated AI for interaction	Prototypes funded by OpenAI & Nvidia	Prototype
Figure 02	Industrial assembly, manufacturing support	~170 cm, hands with 16 DoF, vision system with 6 cameras	AI-driven vision, collaboration with Microsoft–OpenAI–Nvidia, autonomous correction of tasks	Tested in BMW Spartanburg assembly line (automotive assembly)	Pilot
Walker S1	Industrial logistics and production tasks	172 cm, 76 kg, payload 15 kg, multiple tactile sensors, advanced articulation	Semantic navigation (Visual SLAM), imitation learning, precise whole-body control	Factories of BYD, Geely (Zweekr), Nio, Volvo	Commercial pilot
RoBee	Industrial operations (quality control, machine tending, logistics)	Configurable height (135–200 cm), up to 120 kg, 39 DoF, ~8h autonomy, AMR-based mobility	Computer vision, predictive maintenance, integration with company IT systems	About 60 units active in Italian and European factories (mechanical, chemical, logistics, textiles, etc.)	Commercial

Table 2: Comparison of different robot models

3. Methodology and Topic Modelling

The methodology used in this thesis was inspired especially by the approach proposed by Barravecchia, Mastrogiacomo and Franceschini (2021)¹³, who applied topic modelling techniques to analyze the literature on Product-Service Systems (PSS). In that study, the authors showed how text mining and, in particular, the use of Latent Dirichlet Allocation (LDA) algorithms can identify in a systematic way the main research streams and follow their evolution over time. Following the same approach, but adapted to the context of humanoid robotics in manufacturing, the process was divided into four main phases:

1. Dataset collection and construction.
2. Text preprocessing.
3. Application of the STM model (Structural Topic Model).
4. Quantitative and qualitative validation of the results.

3.1 Approach to literature review

To analyze in a structured way the literature on humanoid robots in manufacturing, it was first necessary to collect a large and coherent set of publications. For this reason, Scopus was chosen, one of the most used databases at international level. It includes both journal articles and conference papers, and it is considered the bibliometric database with the largest coverage in engineering and management literature in terms of indexed journals and conference papers (Harzing and Alakangas, 2016).

Using only one source guaranteed data uniformity and helped to avoid problems of duplication or overlap between databases. The search was done with the following query:

¹³ (Barravecchia, F., Franceschini, F., Mastrogiacomo, L., 2021)

(TITLE-ABS-KEY("humanoid robot" OR "anthropomorphic robot") AND TITLE-ABS-KEY(manufactur) OR TITLE-ABS-KEY(industr)) AND PUBYEAR > 1979 AND PUBYEAR < 2026

The query was made to find articles that contained in the title, abstract or keywords references to humanoid or anthropomorphic robots, connected to industrial or manufacturing contexts. The time range was from 1980 until 2025, to have a long historical perspective and include also the most recent works.

The search gave a total of 1,330 documents, that are the reference corpus. For each record the main metadata were extracted: title, abstract, keywords, authors, year of publication and type (journal, book, conference, etc.). This gave not only the texts needed for the analysis, but also contextual information useful to better interpret the results.

In *Figure 13* and *Figure 14* the distribution of articles can be seen by year of publication and by document type. The first chart shows how the interest in humanoids grew especially in the last two decades, with a strong increase after 2010. The second chart shows the prevalence of contributions from conferences, which confirms the evolving nature of the field, where prototypes and preliminary results are often presented.

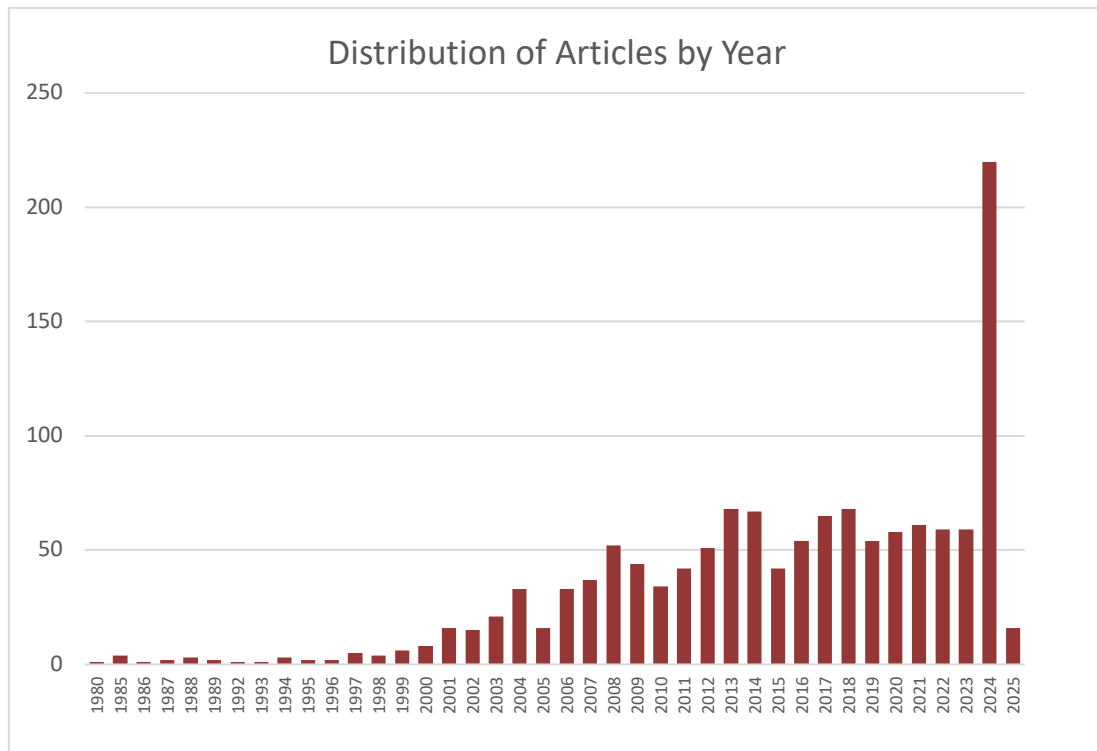


Figure 13: Distribution of the Articles per Year

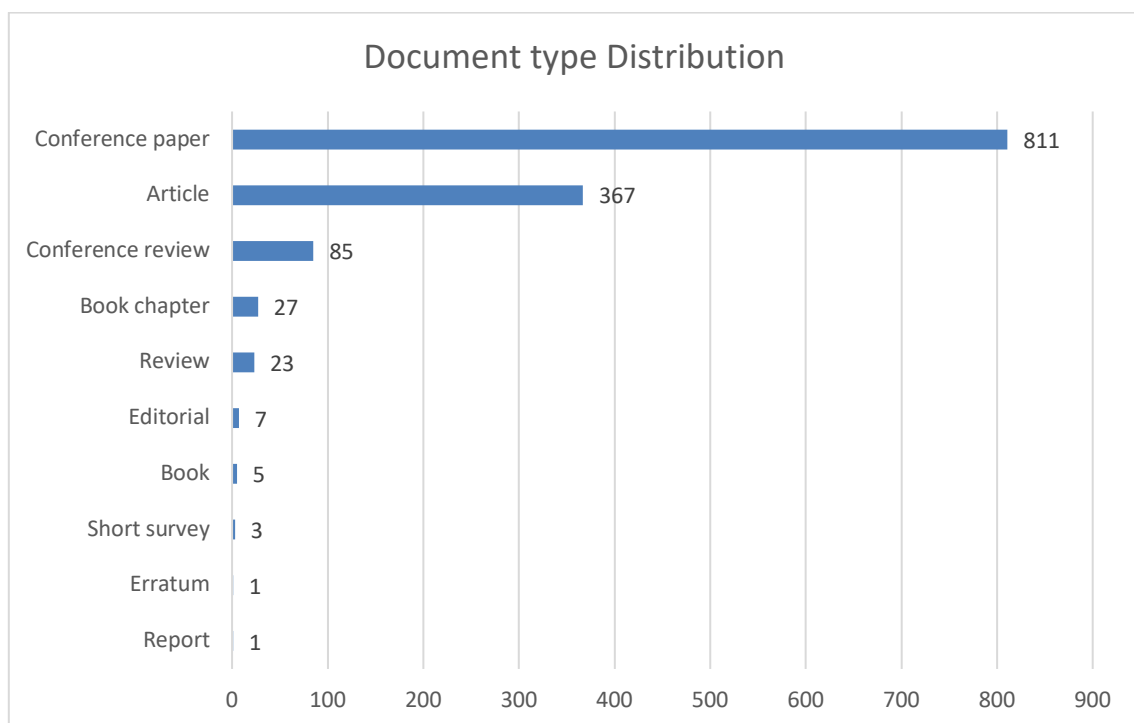


Figure 14: Distribution of the Articles per Document Type

3.2 Management of “proceedings” in the corpus

In the corpus, besides journal articles and single conference papers, there are also records indexed as conference proceedings volumes. This depends on how Scopus works, because sometimes it puts the full volume of a conference as one bibliographic record. These documents were kept guaranteeing completeness of the dataset and coherence with the source, since they are still peer-reviewed contents.

Proceedings have a special feature: one record can include dozens of different contributions, with a very large vocabulary. Because of this, in some cases they are over-represented in specific topics (for example in Topic 9 and in Topic 10), having more weight than a normal article.

To reduce this effect:

- in the labelling and interpretation of topics, priority was given to single articles among the documents with higher weight, while proceedings were considered only as context evidence;
- in the qualitative validation, when a proceedings was among the heaviest documents, it was reported clearly, explaining that the high weight could depend on the “all-inclusive” nature of the record.

This way, the dataset from the database was kept intact, but at the same time there was more transparency on the limits of this type of documents and more reliability in the interpretation of results.

3.3 Pre-processing phase

Raw data from bibliographic databases often contain redundancies, language variants and non-informative terms. To make the corpus ready for computational analysis, a pre-processing step was necessary, following mainly (Barravecchia, F., Franceschini, F., Mastrogiacomo, L., 2021). The main operations were:

1. Removal of stop words, punctuation, numbers and non-content words (e.g., “the”, “and”, “when”, but also generic terms like “paper” or “present”);
2. Elimination of low-frequency words, to reduce noise in the data;
3. Lemmatization, that means reducing words to their base form to avoid dispersion between variants (e.g., “manufacturing” and “manufacturer” → “manufactur”);
4. Substitution of n-grams, that are sequences of words often used together, with one representative term (e.g., “human robot interaction” → “hri”).

This process made the text base more homogeneous, reduced noise and improved the reliability of the analysis.

3.4 Topic modelling and choice of number of topics

To explore the themes present in the corpus, the Structural Topic Model (STM) was applied, an algorithm of topic modelling that can extract latent patterns in the texts and also include contextual variables (Roberts, M. E., Stewart, B. M., & Tingley, D., 2019). The STM is an evolution compared to previous models like Latent Dirichlet Allocation (LDA) (Blei, D. M., Ng, A. Y., & Jordan, M. I., 2003), because it allows to include metadata (for example year of publication or type of document) as covariates, so it can estimate how these influence the prevalence or the content of the topics (Roberts, M. E., Stewart, B. M., & Tingley, D., 2019).

A crucial step was to choose the optimal number of topics (k). Different models with k values between 5 and 100 were generated and evaluated with the Held-out likelihood metric, that measures how well the topic model explains the variability of the corpus. As shown in *Figure 15*, the optimal value was $k = 24$, because at that point the curve became stable and there were no big variations.

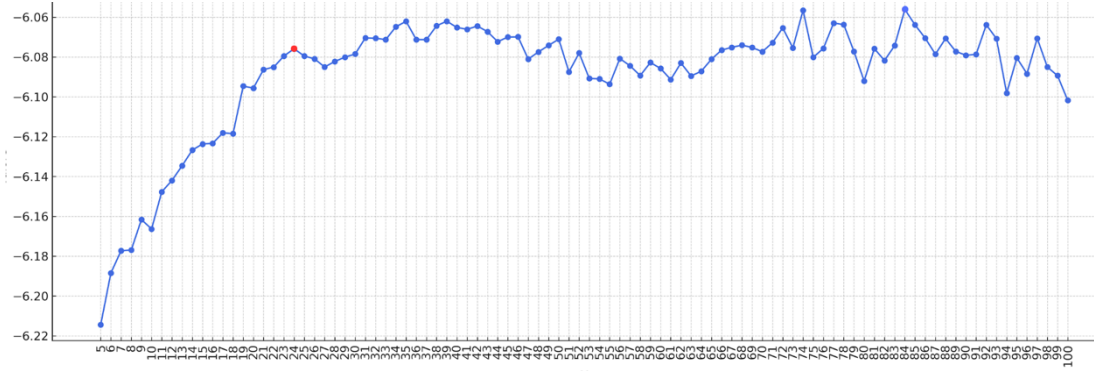


Figure 15: Selection of the Optimal Number of Topics (k)

3.5 Labelling of topics

For each topic, the algorithm produced:

- a set of keywords with different metrics (Highest Prob, FREX, Lift, Score);
- the list of articles with the highest weights.

The labelling was made by analyzing the output of the algorithm with both keywords and the abstracts of the articles with higher weights. This helped to avoid too generic titles and keep semantic coherence with the representative documents.

Example: Topic 14 – Dynamic Locomotion and Stability Control

- Keywords (Highest Prob): robot, walk, control, dynam, model, humanoid, propos, method, stabil, use.
- Representative articles:
 - Methods based on Zero Moment Point (ZMP) to generate stable walking patterns;
 - Balance recovery strategies with steps and center of mass control;
 - Experiments on platforms like HRP-2 and Atlas, with focus on dynamic locomotion and adaptation to external perturbations.

Based on this, the topic was labelled as Dynamic Locomotion and Stability Control in Humanoid Robots. [Table 3](#) shows the chosen labels for the 24 topics.

Topic	Label	Keywords	Sources
1	Affordability and Interface Technologies for Humanoid Robots	will, requir, right, state, reserv, reason, robot, issu, time, cost	2%
2	Open Source Robotics and Decentralized Multi-Robot Collaboration	one, avail, may, open, communic, often, challeng, general, continu, hardwar	1%
3	Design and Evolution of Humanoid Robotic Platforms	humanoid, robot, platform, develop, project, HRP, japan, industry, research	7%
4	Real-Time Control and Servo Architectures in Humanoid Robotics	control, robot, system, implement, design, motor, use, arm, paper, humanoid	4%
5	Humanoid and Collaborative Robotics for Industrial Assembly and Inspection	industry, assembly, automation, device, ta sk, test, operate, drill, inspect, manual	4%
6	Development Pathways in Humanoid Robotics: From Educational Prototypes to Industrial Innovation	robot, technology, industry, research, futu re, engineering, science, university, company, business	6%
7	Human Perception and Psychological Effects in Human-Humanoid Robot Interaction	human, movement, collabor, affect, perfo rm, studi, robot, perceiv, observ, particip	4%
8	Mobile Manipulation and Reconfigurable Robotic Workstations	robot, system, mobil, manipul, paper, public, switzerland, describ, tech, tran	4%
9	Mechanical Systems Analysis and Simulation in Robotics and Automation	base, system, analysi, design, studi, resear ch, model, simul, method, control	3%
10	Human-Robot Interaction, Intelligent Agents and Immersive Technologies	interact, system, intellig, model, learn, robot, virtual, agent, use, includ	4%
11	Kinematics and Stiffness Optimization of Anthropomorphic Robot Arms	joint, arm, kinemat, manipul, robot, model, use, posit, invers, stiff	6%
12	Trajectory Generation and Task Execution in Humanoid Robots	motion, robot, plan, method, task, generat, trajectori, human, humanoid, propos	6%
13	Design and Functionality of Robotic Hands for Dexterous Manipulation	hand, finger, grasp, dexter, gripper, objec t, mechan, function, grip, underactu	4%
14	Dynamic Locomotion and Stability Control in Humanoid Robots	robot, walk, control, dynam, model, humanoid, propos, method, stabil, use	6%
15	Visual Sensing and Object Localization in Humanoid and Mobile Robotics	use, algorithm, data, robot, object, method, imag, propos, camera, accuraci	5%
16	Robotic Additive Manufacturing and Process Monitoring	materi, manufactur, process, measur, paramet, surfac, use, system, laser, composit	3%
17	Emotion Recognition and Expression in Humanoid Robot Interaction	robot, express, emot, human, interact, head, facial, communic, humanoid, face	3%
18	Navigation and Task Allocation in Heterogeneous Humanoid Robot Teams	robot, task, learn, use, approach, demonstr, propos, simul, perform, navig	5%
19	Mechanical Design and Additive Manufacturing Optimization in Humanoid Robots	design, mechan, robot, develop, optim, manufactur, structur, use, addit, process	4%
20	Flexible Tactile Perception Systems in Human-Robot Interaction	sensor, sens, forc, use, robot, tactil, skin, pressur, can, fabric	4%
21	Actuation and Transmission Systems in Humanoid Robotics	actuat, robot, drive, torqu, mechan, muscl, joint, high, use, design	4%
22	Robotic Automation and Smart Manufacturing in Machining and Welding Processes	use, product, machin, robot, tool, weld, process, technolog, method, can	4%
23	Remote Teleoperation and Full-Body Control of Humanoid Robots for Industrial Vehicle Operation	control, robot, oper, environ, task, system, perform, interfac, human, teleoper	4%
24	Anthropomorphism in Robots: Different Preferences Depending on the Application Domain	robot, anthropomorph, interact, human, design, differ, human-robot, trust, social, industri	3%

Table 3: Topic labels, keywords and sources

3.6 Model validation

Validation was done with two levels, to guarantee robustness and reliability of the results.

1. Dynamic threshold: For each topic, the weights of documents were filtered with a threshold calculated as:

$$DT_i = Q3_i + (1.5 \cdot IQR_i)$$

where $Q3_i$ is the third quartile and IQR_i is the interquartile range. In this way, only articles with weight higher than the threshold were considered representative.

2. Manual validation: A sample of 50 articles was analyzed manually, comparing the topic assignment by the algorithm with the assignment made by human reviewers.

The results were put in a confusion matrix (with true positives, true negatives, false positives and false negatives), and standard evaluation metrics were calculated as shown in the [Table 4](#) (Powers, 2011):

Accuracy	0.94
Precision	0.65
Recall (Sensitivity)	0.92
Specificity	0.94
F1 Score	0.76
Miss Rate	0.08
Fall-out	0.06
NPV (Negative Predictive Value)	0.99
FDR (False Discovery Rate)	0.35
FOR (False Omission Rate)	0.01

Table 4: Standard evolution metrics

Almost all values are inside the standards generally accepted in literature, confirming the solidity of the model. The only indicator with a problem is the False Discovery Rate (FDR), that is quite high. This is because the algorithm tends to recognize more topics than the human reviewers, increasing false positives. Anyway, the high overall accuracy and the very low FOR show that the model can identify almost all relevant documents, minimizing exclusion errors.

3.7 Summary

In summary, the methodology made possible to build a large and representative dataset, process it to guarantee quality and coherence, and explore it with STM, which produced 24 topics that were well interpretable. The labelling step, based on keywords and representative articles, gave coherent titles to the clusters. The validation, with both statistical criteria (dynamic threshold) and human review, confirmed the reliability of the results, with high accuracy and recall. The next analyses (Chapter 4 – Topic Analysis) are therefore based on solid methodological foundations.

4. Topic Analysis

4.1 Topic 1- Affordability and Interface Technologies for Humanoid Robot

4.1.1 Topic description

Topic 1 is about the development of cost-effective humanoid robots together with the design of intuitive interfaces for their control. The research shows that these two aspects are connected: making robots cheaper and accessible is important, but also giving them easy interaction systems is necessary to really use them in daily life. The works talk about affordable robotic platforms for industrial, home and entertainment tasks, and at the same time they study new interfaces like stereoscopic displays, virtual reality (VR), and immersive control systems. These interfaces help to reduce cognitive effort and improve human–robot interaction.

In summary, the topic links the economic sustainability of humanoid robots with technological solutions that make them more usable and accessible, showing one combined movement toward democratization of robotics and improvement of usability.

4.1.2 Most Relevant Articles

Based on topic weights, the five most influential publications within this topic are:

1. **Urey et al. (2011)** – *State of the art in stereoscopic and autostereoscopic displays* – give a wide review of stereoscopic, autostereoscopic, and head-mounted display technologies. These systems are important for immersive human–robot interfaces, because they give better three-dimensional awareness and more natural control in teleoperation. The paper shows technical problems like crosstalk, resolution limits, and accommodation–convergence conflicts, but also new solutions that improve usability and user comfort.
2. **Dincer et al. (2019)** – *Communication of cost oriented humanoid robot* – introduce the idea of Cost Oriented Humanoid Robots (COHR), with focus on communication between multiple humanoid robots. They propose a leader–follower model for synchronized operations, that can be used in industrial and home applications at lower cost. The paper shows that affordability does not always mean less functionality, if there are strong communication protocols.
3. **Kopacek (2012)** – *Cost oriented humanoid robots* – continues the COHR idea by classifying humanoid robots in four groups: professional, research, toy, and cost-oriented. The work explains the need for affordable humanoids, placed between research prototypes and commercial toys. The author imagines a market where humanoid robots are both cheap enough and socially useful in daily life.
4. **Hirukawa et al. (2007)** – *Field and service applications – Dinosaur robotics for entertainment applications* – describe the development of

dinosaur-shaped humanoid robots presented at the World Exposition. Besides entertainment, the project showed how humanoid robots can engage people and share scientific knowledge. The study also explains cost problems, because the prototypes needed millions of dollars for development and production, making clear the importance of cost reduction for future scalability.

5. **Allspaw et al. (2019)** – *Design of Virtual Reality for Humanoid Robots with Inspiration from Video Games* – study how VR can be used in humanoid robot teleoperation. Inspired by video games, they propose VR-based control interfaces that reduce operator effort and improve awareness of the situation. The work shows how immersive technologies can connect complex robotic systems with easier human use.

4.1.3 Temporal Trends (IMPT per Year)

- **1980–1995:** the topic is very marginal, with only a few papers and almost zero IMTP values. Early studies are mostly theoretical, with basic ideas on interfaces and first attempts to make robots cheaper, but they stayed isolated.
- **1995–2005:** a first growth appears, thanks to more work on human–machine interfaces and on cost reduction in robotic systems. This shows a change from basic research to more applied studies, in line with the growth of service and collaborative robotics.
- **2005–2015:** the topic grows steadily, supported by research on usability, ergonomic design, and the use of sensors and simple interfaces. The goal is to make humanoid robots useful in education, at home, and in industrial contexts.
- **2018–2022:** the topic reaches the highest IMTP peak, with works that connect low cost, interface design, and real applications (like assistance, rehabilitation, and social interaction). This shows the maturity of the field: from experimental to a real design requirement.

- **After 2022:** the trend becomes stable, meaning that affordability and interface technologies are not “new topics” anymore but a standard requirement in humanoid robot development.

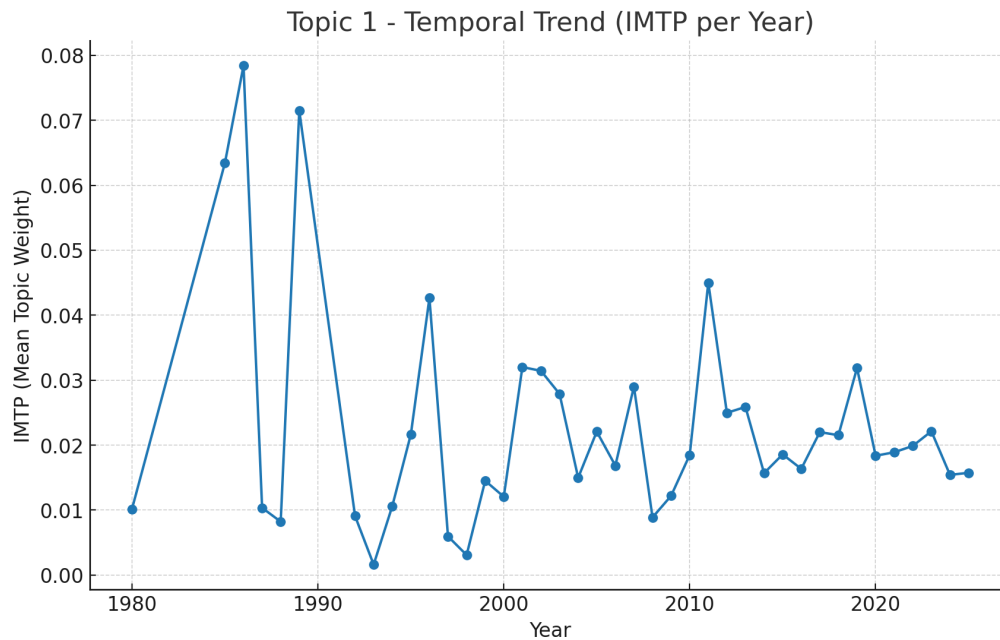


Figure 16: Topic 1: Affordability and Interface Technologies for Humanoid Robot (IMTP per Year)

In short, Topic 1 shows the path of an enabling technology: from marginal in the 1980s, to central between 2010 and 2020, and now a consolidated requirement. The graph makes this very clear, with near-zero values until the early 2000s, steady growth until 2020, and stabilization in the last years.

4.2 Topic 2 - Open-Source Robotics and Decentralized Multi-Robot Collaboration

4.2.1 Topic Description

Topic 2 is about the role of open-source robotics frameworks and decentralized collaboration in multi-robot systems. Unlike centralized systems that need constant communication and control, research here shows the benefits of distributed decision-making, better resilience to failures, and adaptation to different environments. Open-source platforms like ROS (Robot Operating System) and new toolkits are important

because they make it easier for researchers, in both academia and industry, to work and collaborate globally.

An important part of this topic is the integration of different robot types, like ground vehicles and aerial robots, into teams that can work even with weak communication. Gossip-based protocols, distributed optimization, and modular open-source tools are key strategies to reach scalability and robustness. In general, Topic 2 shows a double trend: open-source access helps democratization, while decentralized systems improve efficiency. Together, they are shaping the next generation of collaborative robotics.

4.2.2 Most Relevant Articles

Based on topic weights, the five most influential publications within this topic are:

1. **Cladera et al. (2024)** – *Enabling Large-scale Heterogeneous Collaboration with Opportunistic Communications*
This paper introduces MOCHA, a framework for resilient multi-robot collaboration based on gossip communication protocols. It shows scalability across different robots with unreliable communication, tested both in real-world and simulation. The open-source release shows the importance of community-driven development.
2. **Saravanos et al. (2023)** – *Distributed Differential Dynamic Programming Architectures for Large-Scale Multiagent Control*
This work proposes decentralized control using differential dynamic programming and ADMM consensus. It shows scalability to thousands of robots and better efficiency compared to centralized methods. Real hardware tests confirm the practical value.
3. **Dahiya et al. (2007)** – *Tactile Sensing Arrays for Humanoid Robots*
Even if focused on tactile sensing, this paper places the work inside the open-source robotics community. It proposes modular sensor arrays and shows how open collaboration and accessible hardware can help innovation in humanoid robotics.
4. **Rozlivek et al. (2021)** – *Multisensorial Robot Calibration Framework and Toolbox*

This work presents a unified open-source calibration toolbox for humanoid robots and industrial manipulators. By integrating multiple sensors and offering a MATLAB toolbox, it supports reproducibility and accessibility in robotics research.

5. **Takanobu et al. (1999)** – *Remote Interaction between Human and Humanoid Robot*

This early work studies teleoperation and remote collaboration, anticipating later work on distributed control. Even if limited by the technology of that time, it gave important first insights about communication in humanoid robotics.

4.2.3 Temporal Trends (IMTP per Year)

The evolution of Topic 2, measured through the Index of Mean Topic Proportion (IMTP) across years per year, highlights several stages:

- **2000–2010:** the topic is almost absent, with very few papers on humanoid robots and advanced manufacturing. Most work was conceptual.
- **2015–2020:** the topic expands clearly, thanks to Additive Manufacturing technologies and the need for flexible automation. Important cited works appear, especially about process monitoring (for example, height control in laser metal deposition).
- **2020–present:** the topic becomes stronger, with works combining humanoid robots and AM not only to make complex parts but also to improve quality in real time. This shows the shift from experiments to established practice in smart manufacturing.

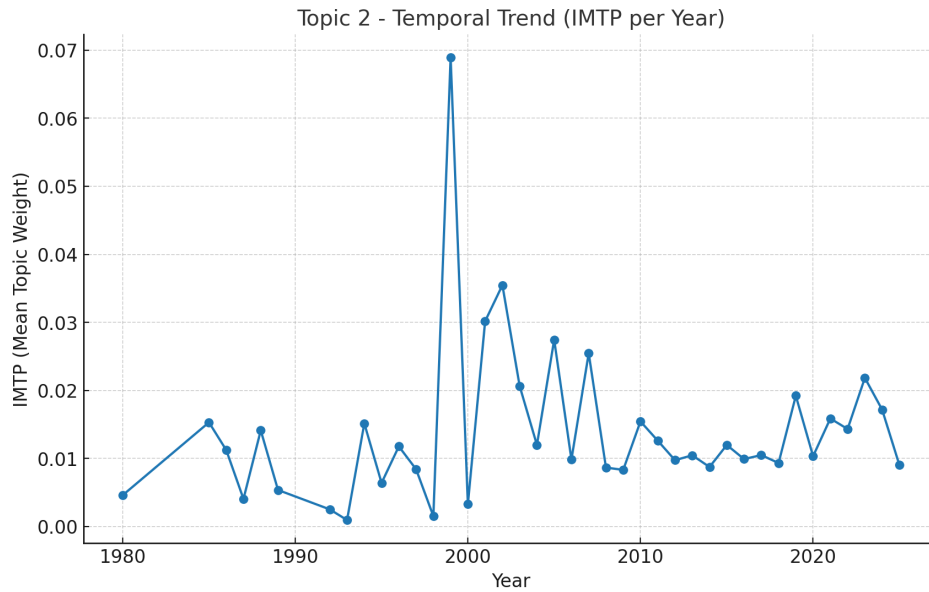


Figure 17: Topic 2: Open-Source Robotics and Decentralized Multi-Robot Collaboration (IMTP per Year)

Overall, Topic 2 illustrates the path of a growing research area, evolving from marginal beginnings to a mature field at the intersection of additive manufacturing and robotic control.

4.3 Topic 3 - Design and Evolution of Humanoid Robotic Platforms

4.3.1 Topic Description

Topic 3 is about the design, evolution, and technology of humanoid robotic platforms, with focus on big government-funded projects like the Humanoid Robotics Project (HRP) in Japan. The research looks at the main challenges in humanoid platform design, such as biped locomotion, whole-body motion, kinematic modules, control systems, and electrical systems.

A key point is the step-by-step development of humanoid prototypes (HRP-1 → HRP-2), showing how new generations improved stability, robustness, and functions. These platforms were not only research robots but also testbeds for applications in industry, services, and social areas. The topic shows the historical and technical base of humanoid robotics, connecting the first prototypes to later real-world applications.

4.3.2 Most Relevant Articles

Based on topic weights, the five most influential publications are:

1. **Kaneko et al. (2002)** – *Design of prototype humanoid robotics platform for HRP*
This paper presents the development of the HRP-2 prototype, funded by METI (Japan). It explains improvements in biped locomotion, robustness against tipping, and whole-body control. It also gives technical details, showing HRP-2's ability to work outdoors and on uneven terrain.
2. **Kaneko et al. (2002)** – *Design of advanced leg module for humanoid robotics project of METI*
This work focuses on the advanced leg module of HRP-2, with kinematics, motion control, and simulations used to optimize design. It shows how modular improvements helped HRP-2 walk on rough terrain and stay stable.
3. **Tanie & Yokoi (2003)** – *Humanoid and its potential applications*
This article looks at industrial and social uses of humanoid robots inside the HRP project. The authors identify five areas, from industrial maintenance to service industries, showing how humanoids can create new markets and value for society.
4. **Kanehira et al. (2002)** – *Design and experiments of advanced leg module (HRP-2L) for humanoid robot development*
This paper presents experiments on the HRP-2L leg module, adding real tests to the theoretical designs. Results confirm better locomotion stability and resistance to falling, giving a base for future humanoid systems.
5. **Kaneko et al. (2004)** – *Humanoid robot HRP-2*
A key paper that puts together the full HRP-2 development, with details on mechanical design, electrical systems, control, and locomotion. HRP-2 could walk on narrow paths, deal with uneven

terrain, and recover from tipping, becoming a milestone in humanoid robotics.

4.3.3 Temporal Trends (IMTP per Year)

- **1980–1995:** the topic is marginal, with only a few pioneering contributions focused on the first experimental platforms like WABOT, which remained isolated cases.
- **1995–2005:** the weight grows fast, with a peak between 2000 and 2005. In these years emblematic robots such as ASIMO and HRP were presented, attracting strong attention on mechanical design and structural evolution of humanoids.
- **2005–2015:** the trend stays consistent but starts to slowly decrease. This phase corresponds to the consolidation of the projects started before, with a standardization of architectures and more focus on detailed engineering aspects.
- **2015–today:** the topic stabilizes at medium values, with less explosive interest compared to the past but still relevant. In this period, new platforms like Atlas and Digit appear, shifting the evolution more toward dynamic locomotion and integration with industrial applications.

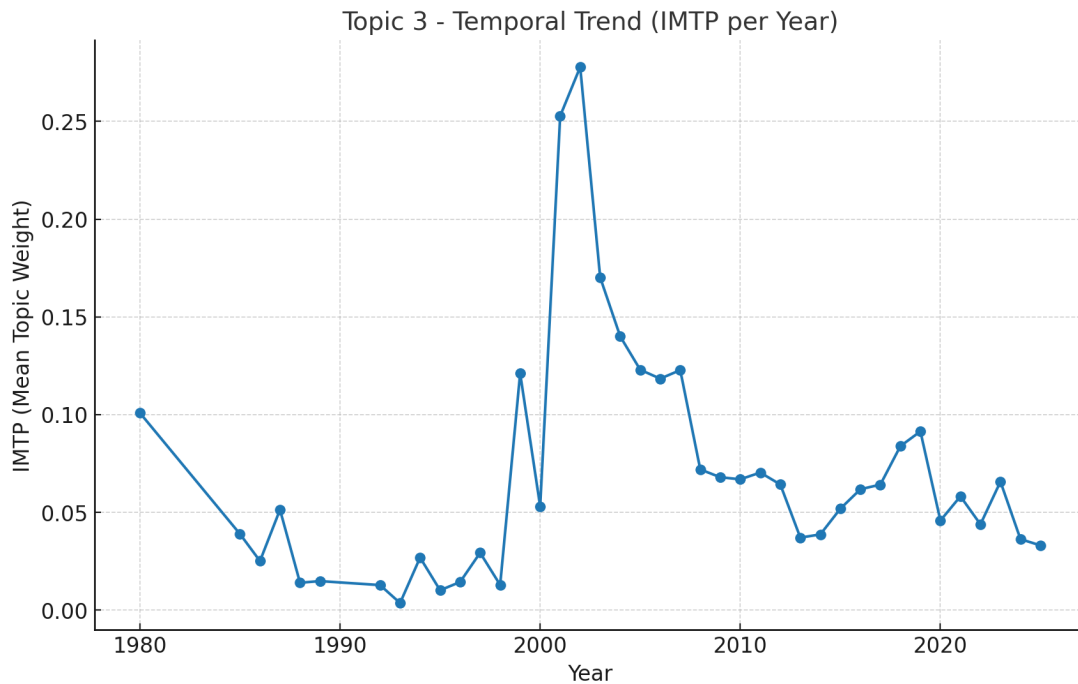


Figure 18: Topic 3: Design and Evolution of Humanoid Robotic Platforms (IMTP per Year)

In short, the trajectory of Topic 3 shows the historical path of humanoid platform development: from early experiments, to a peak with the design and launch of iconic robots, and finally to a phase of consolidation and maturity that opens the way to practical applications in manufacturing.

4.4 Topic 4 - Real-Time Control and Servo Architectures in Humanoid Robotics

4.4.1 Topic Description

Topic 4 is about how humanoid robots are controlled and coordinated in real time. The focus is on the control stack: embedded and distributed architectures (like FPGA modules and dual-bus networks), servo loops for position, velocity, and force control, and extra systems that keep robots safe during motion. Research in this topic goes from high-speed communication and hardware-accelerated controllers to low-cost designs with Arduino and feedback systems for protection.

In short, the topic is about making humanoid motion reliable, fast, and robust: from the bus that sends commands, to the chip that calculates the control, to the motor that closes the loop.

4.4.2 Most Relevant Articles

Based on topic weights, the five most influential publications are:

1. **Li (2013)** – *FPGA-based module design for PM linear motor control, applied to a music-playing humanoid*
This paper proposes a hierarchical control system with a PC host and FPGA-based local controllers, each managing closed-loop velocity and position of actuators. Tested on a piano-playing humanoid robot, it shows how FPGA acceleration ensures precise synchronization of many degrees of freedom, allowing complex multi-finger and two-hand tasks in real time.
2. **Cha & You (2009)** – *Dual control network method for efficient real-time humanoid control system*
This work presents a dual-network design combining IEEE-1394 (high bandwidth) and CAN bus (noise resistance) to improve humanoid control. Tested on the MAHRU platform, it reduces delay and increases reliability, showing that network design has a direct impact on real-time servo control.
3. **Huang et al. (2020)** – *Robot Auxiliary Suspension and Control Feedback System*
This paper introduces an auxiliary suspension and feedback system using PMSM motors with Field-Oriented Control (FOC). It gives fast torque and position response, improving stability and safety. With PI-based current control, it supports adaptive force regulation and shows the role of auxiliary systems in safe humanoid motion.
4. **Kim & Jung (2009)** – *Joint control of ROBOKER arm using a neural chip embedded on FPGA*
This study uses a radial basis function (RBF) neural controller on FPGA to control the dual-arm humanoid ROBOKER. The neural chip allows online learning and nonlinear function processing, working better than

PD controllers for trajectory tracking. It is one of the first examples of combining neural networks with FPGA for real-time adaptive control in humanoids.

5. **Li & Wu (2013)** – *Research and design of a small humanoid robot based on Arduino*

This paper focuses on a low-cost humanoid controlled with Arduino. The robot supports multiple servos and can execute pre-programmed actions offline, without external computation. It shows the trade-off between low cost and advanced functions, proving that even simple hardware can give reliable humanoid motion for education and prototyping.

4.4.3 Temporal Trends (IMTP per Year)

Using the weights provided for Topic 4, the Index of Mean Topic Proportion (IMTP) over time shows:

- **1990–2000:** the topic is marginal, with very few studies and almost zero IMTP values. Early works studied robotic walking but were far from real use.
- **2005–2015:** the topic grows, thanks to more interest in biped robots and better balance-control methods. This period saw the first stable prototypes and studies on adaptive gait and interaction with the environment.
- **2018–present:** the topic peaks, with many publications and high IMTP values. Biped locomotion moved from experiment to a central research area, linked to competitions like RoboCup and applications in service and assistive robotics.

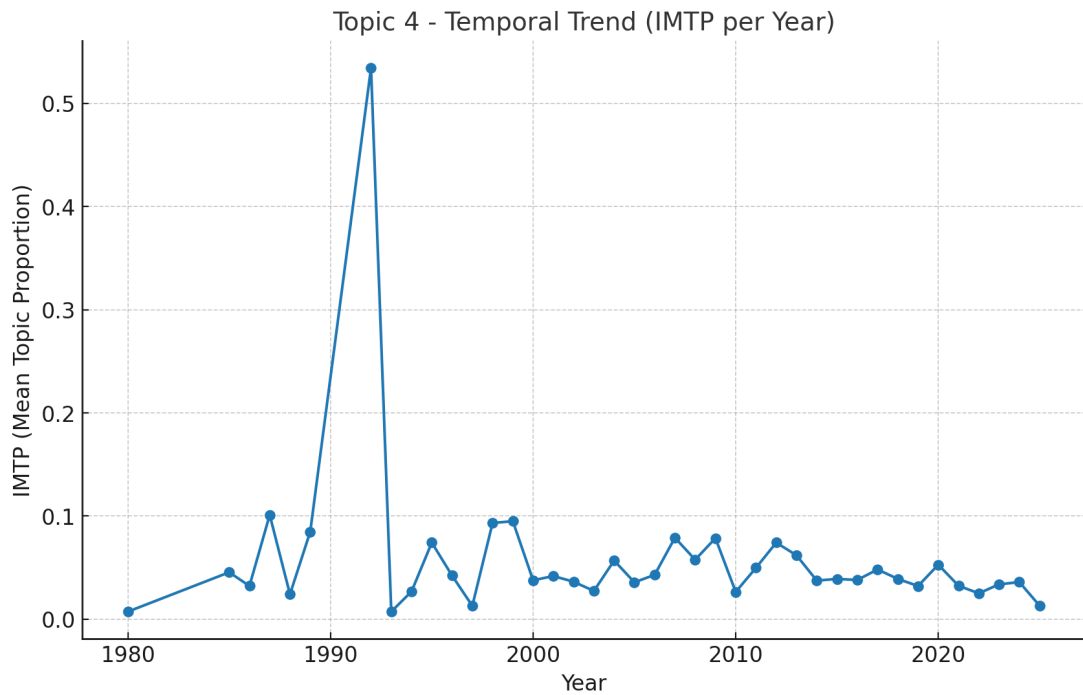


Figure 19: Topic 4: Real-Time Control and Servo Architectures in Humanoid Robotics (IMTP per Year)

Overall, Topic 4 illustrates the shift of bipedal locomotion from a lab curiosity to a cornerstone of modern humanoid robotics.

4.5 Topic 5 - Humanoid and Collaborative Robotics for Industrial Assembly and Inspection

4.5.1 Topic Description

Topic 5 looks at how humanoid and collaborative robots are used in industrial assembly and inspection. The research focuses on how robots can replace or support humans in dangerous, repetitive, or very precise tasks. There are two main parts: (i) the development of flexible, low-cost robotic systems made for industrial manufacturing, like drilling and machining, and (ii) teleoperation systems that extend human control into remote or risky places, like oil and gas facilities.

The topic also includes recent works on smart end-effectors with embedded intelligence, which help collaboration in unstructured environments, and conceptual studies about digital transformation and AI in industrial collaboration. Overall, Topic

5 shows the steady shift of humanoid and collaborative robotics from lab prototypes to scalable industrial applications.

4.5.2 Most Relevant Articles

Based on topic weights, the five most influential publications are:

1. **Naranjo et al. (2018)** – *Flexible Architecture for Transparency of a Bilateral Tele-Operation System implemented in Mobile Anthropomorphic Robots for the Oil and Gas Industry*
This paper presents a bilateral teleoperation system using anthropomorphic robots for inspection and maintenance in oilfields. The architecture uses the MQTT protocol for efficient bandwidth and real-time work, while a VR interface gives immersive operator control. It shows how humanoid robots can extend human abilities in extreme environments.
2. **Marino et al. (2016)** – *A General Low-Cost and Flexible Architecture for Robotized Drilling in Aircraft Assembly Lines*
The authors propose a cost-effective robotic solution for drilling tasks in aircraft assembly. They combine a commercial manipulator, a force sensor, and a standard drilling tool, making the system flexible and adaptable to existing lines. It shows the potential of humanoid-like robots to increase automation and reduce human workload.
3. **Schrettenbrunner (2024)** – *The Sixth Organizational Maturity Level and Autonomous Digital Transformation for Nonlinear or Exponential Growth*
This review introduces the Plan–Predict–Act (PPA) cycle, an AI-based management model for autonomous collaboration in industry. Even if more conceptual, it connects to collaborative humanoid robotics by showing how automation, AI, and robotics can be part of digital transformation strategies on an organizational level.
4. **Bianco et al. (2024)** – *Smart Drill: An Autonomous Drilling End-Effector with Embedded Sensing and Intelligence for Mobile and Collaborative Robots*

This work develops the Smart Drill, an autonomous drilling tool with sensors, computation, and power management inside it, made for cobots and mobile robots. By moving low-level control into the tool itself, it allows semi-autonomous drilling in unstructured and collaborative industrial settings.

5. **Atzeni et al. (2018)** – *Countering Android Malware: A Scalable Semi-Supervised Approach for Family-Signature Generation*

Even if focused on cybersecurity, this work is included for its method on automation and scalability. Its value is in showing how industrial robotic systems could use AI frameworks for anomaly detection and resilience.

4.5.3 Temporal Trends (IMTP per Year)

The evolution of Topic 5, measured via the Index of Mean Topic Proportion (IMTP), highlights the following dynamics:

- **Until 1990:** the topic is almost absent, with very few papers and IMTP values close to zero. Fine manipulation was not a priority, as robotics focused more on locomotion and structure.
- **1995–2005:** the first real studies appear, mostly on mechanical models of the hand and early control for fingers and grasping. Interest was limited but slowly growing.
- **2008–2015:** the topic expands, with more articles and higher weights. This period saw the first complex robotic hand prototypes for real interaction, and more work on tactile sensing.
- **2018–present:** the topic peaks. Manipulation becomes central for humanoid autonomy, with strong links to assistive and industrial robotics. Recent work focuses on dexterity, adaptive grasping, and new sensors, showing that manipulation is now seen as a key challenge to make robots really useful in daily life.

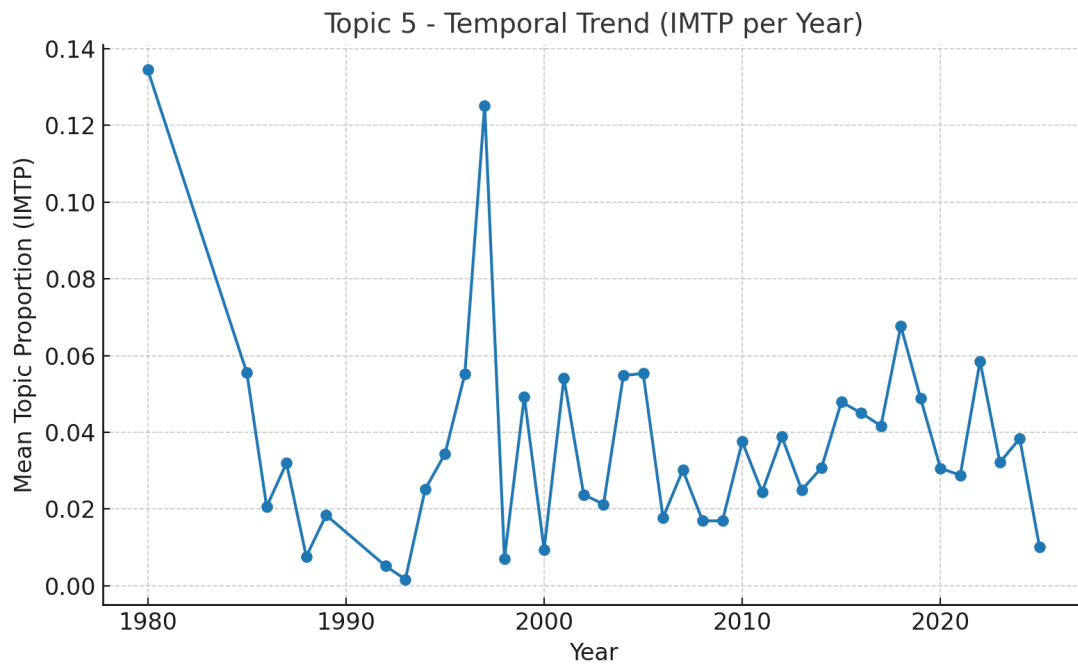


Figure 20: Topic 5: Humanoid and Collaborative Robotics for Industrial Assembly and Inspection (IMTP per Year)

In short, Topic 5 illustrates how manipulation has evolved from a side topic to a cornerstone of humanoid robotics, now seen as essential for practical and interactive tasks.

4.6 Topic 6 - Development Pathways in Humanoid Robotics: From Educational Prototypes to Industrial Innovation

4.6.1 Topic Description

Topic 6 looks at how humanoid robotics changed over time, starting from small prototypes and robots used in education, until real industrial and commercial solutions. The focus is not only on technical progress, but also on the people and companies that pushed this field. Interviews with important figures like Rodney Brooks, Mark Tilden, Maja Matarić, and Jun Ho Oh give useful views on how research, startups, and industrial needs worked together to make progress.

This topic is not about just one technical problem. It is more about the development path: how experimental robots in universities became tools for students, how

companies transformed prototypes into real products, and how research created new uses in healthcare, industry, and society. In short, Topic 6 shows the change of humanoid robotics from something only for labs to a global innovation field.

4.6.2 Most Relevant Articles

Based on topic weights, the five most influential publications are:

1. **Pransky (2015)** – *The Pransky interview: Dr Rodney Brooks, Robotics Entrepreneur, Founder and CTO of Rethink Robotics*

This article is an interview with Rodney Brooks, who worked at MIT, iRobot, and Rethink Robotics. His projects like Roomba and Baxter had a big impact. He explains how he moved from academic work to business, and he talks about the problems of making robotics into real products. The interview shows how ideas from labs can become products used worldwide.

2. **Pransky (2014)** – *The Pransky interview: Dr Mark W. Tilden, Robotics Physicist*

This interview is about Mark Tilden, who created BEAM robotics and simple biomorphic systems. He moved from research at Los Alamos National Lab to consumer robotics, especially with the toy industry. His story shows how experimental robots can become big commercial success.

3. **Kopacek (2013)** – *Development trends in robotics*

This review explains the main trends in robotics. It shows the move from fixed industrial robots to mobile, cooperative, and humanoid robots. It also talks about bio-inspired and socially assistive robots, and the challenges of putting robots in daily life.

4. **Pransky (2019)** – *The Pransky interview: Dr Maja Matarić, Pioneer in Socially Assistive Robotics*

This work is an interview with Maja Matarić, who is very important in socially assistive robotics. She explains her research about robots that help people with autism, Alzheimer's and other conditions. Her work

shows how robots can be used not only in labs, but also to support people and improve their lives.

5. **Pransky (2017)** – *The Pransky interview: Dr Jun Ho Oh, Professor and Director of Humanoid Robot Research Center, KAIST*
This interview is about Jun Ho Oh, who created the HUBO robots at KAIST. His group worked for many years, and in 2015 they won the DARPA Robotics Challenge. His story shows how long research and strong projects can bring international recognition and industrial results.

4.6.3 Temporal Trends (IMTP per Year)

The temporal evolution of Topic 6, based on the Index of Mean Topic Proportion (IMTP), shows a clear trajectory of maturation:

- **Until 1995:** the topic was almost not present, with very few works. Computer vision was still very new and not really connected to humanoid robotics.
- **2000–2010:** the topic started to grow, with first methods for object and human recognition. These were often tested on small humanoids in labs.
- **2012–2017:** there was a strong increase. Vision became very important for tasks like navigation, human–robot interaction, and facial recognition.
- **2018–present:** the topic reached its maximum point. Deep learning and neural networks changed perception in humanoids, making it much stronger and more useful in real situations, like social robots and service robotics.

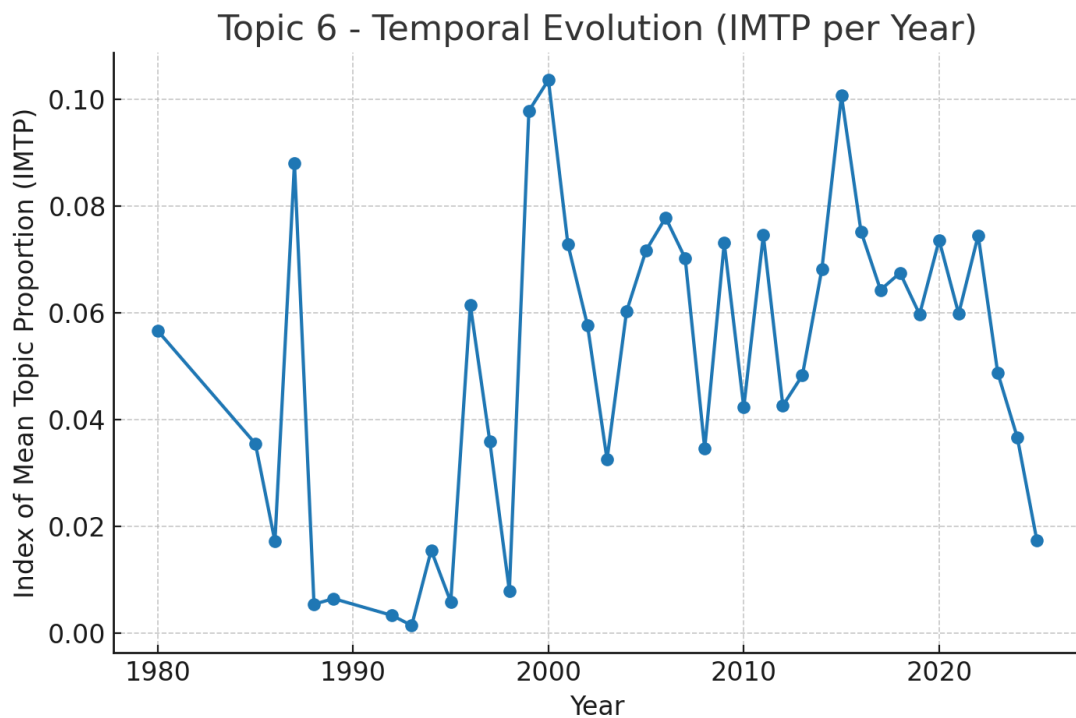


Figure 21: Topic 6: Development Pathways in Humanoid Robotics: From Educational Prototypes to Industrial Innovation (IMTP per Year)

Overall, Topic 6 highlights how computer vision evolved from a supporting tool into a central enabler of autonomy and interaction in humanoid robots.

4.7 Topic 7 - Human Perception and Psychological Effects in Human–Humanoid Robot Interaction

4.7.1 Topic Description

Topic 7 looks at how people see and react to humanoid robots, with focus on social interaction, motor effects, and anthropomorphism. It studies the psychological and neurological parts of human–robot interaction, like motor interference, perceived intelligence, and biological motion recognition. Research in this area shows that humanoid robots can create similar behavioural and cognitive reactions as humans do, but also shows limits and biases, for example gender differences, robot design, or realism of movements. In general, the topic shows how human perception is very important for the acceptance and effectiveness of humanoid robots, both as co-workers and as social or assistive agents.

4.7.2 Most Relevant Articles

Based on topic weights, the five most influential publications are:

1. **Vasalya et al. (2018)** – *Distinct Motor Contagions during and after Observation of Actions by a Humanoid Co-Worker*

This study shows how observing robot actions can change human movements, both during the interaction (online contagion) and after (offline contagion). In an industrial co-worker context, humanoid robots influenced human movement speed and frequency in ways similar to human colleagues, proving a strong connection between human and robot actions.

2. **Liao et al. (2024)** – *Why not work with anthropomorphic collaborative robots?*

The authors analyse why some workers do not accept collaborative robots. They found that perceived intelligence and self-efficacy are important factors. With a study of 323 participants, they show that anthropomorphic design can increase acceptance, but also sometimes make people feel threatened. The results give ideas for designing cobots that are efficient and also socially acceptable.

3. **Abel et al. (2022)** – *Anthropomorphic or non-anthropomorphic? Effects of biological sex in observation of actions*

This paper uses fMRI to study how men and women perceive robot and human actions differently. Results show that male and female participants use different neural pathways when observing humanoid vs. robotic actions. This means gender plays a role in how people process anthropomorphism.

4. **Oztop et al. (2004)** – *Human-humanoid interaction: Is a humanoid robot perceived as a human?*

One of the first experimental studies. It compares human–human interaction with human–humanoid interaction, measuring motor interference effects. Results show that humanoid robots can create

interference patterns similar to humans, suggesting shared processes in perception. This study gave one of the first frameworks for testing human reactions to humanoid robots.

5. **Kupferberg et al. (2011)** – *Biological movement increases acceptance of humanoid robots as human partners in motor interaction*

This paper shows that humanoid robots moving with human-like timing and smoothness are more accepted as partners than robots moving with constant, artificial speed. The results confirm that natural biological motion helps to improve human–robot interaction.

4.7.3 Temporal Trends (IMTP per Year)

The temporal evolution of Topic 7, measured through the Index of Mean Topic Proportion (IMTP), highlights the following trajectory:

- **Until 1995:** the topic was almost not present, with IMTP values close to zero and very few studies.
- **1998–2008:** the first growth phase started, thanks to algorithms like SLAM (Simultaneous Localization and Mapping), that let robots build maps while moving.
- **2010–2016:** consolidation phase, with more publications and higher weights. In these years, humanoid robots started to use sensors like LIDAR, stereo cameras, and RGB-D systems (like Kinect), which were important for indoor navigation and perception.
- **2018–present:** the topic reaches the peak. New works use visual SLAM, deep learning, and advanced sensor fusion. The focus is now on navigation in complex and dynamic environments, like homes, hospitals, and public spaces.

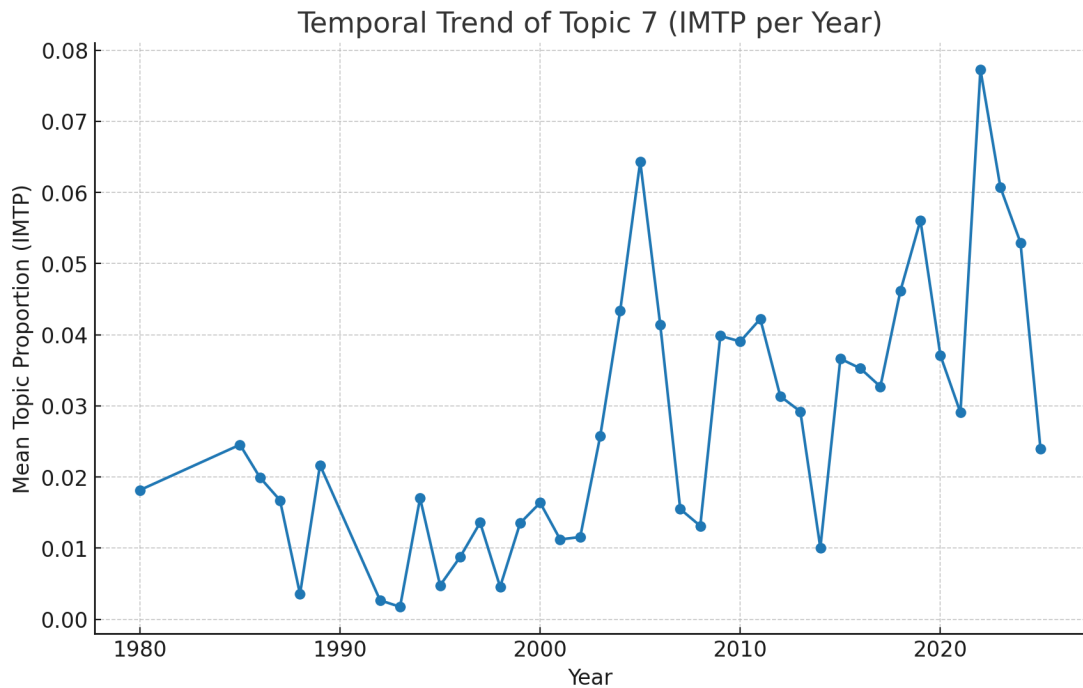


Figure 22: Topic 7: Human Perception and Psychological Effects in Human–Humanoid Robot Interaction (IMTP per Year)

In short, Topic 7 illustrates how autonomous navigation evolved from an unexplored problem to a core capability of humanoid robotics, now enabled by advanced sensors and intelligent algorithms.

4.8 Topic 8 - Mobile Manipulation and Reconfigurable Robotic Workstations

4.8.1 Topic Description

Topic 8 looks at the design and use of multi-robot systems and flexible workstations. The focus is on how to integrate industrial and humanoid robots in modular environments, making them more adaptable and efficient. Applications include palletizing, assembly, collision management, and mobile manipulation. Some early studies also looked at humanoid robots in service or entertainment, like robotic musicians. In general, this topic shows the move from static, single-robot setups to dynamic systems where multiple robots can work together and adapt to different industrial and research needs.

4.8.2 Most Relevant Articles

Based on topic weights, the five most influential publications are:

1. **Koukolová (2014)** – *Variability of workplace structures with SCARA robot for palletizing and sorting objects*
This paper shows a modular workplace design for palletizing and sorting. It explains how SCARA robots can be reconfigured and adapted for different production requirements.
2. **Balá et al. (2014)** – *Proposal of multirobotic system with two robots*
Describes a system with two robots: a manipulation robot (OTC Daihen AXV6) and an assembly robot (Motoman SDA 10F). The robots are integrated with conveyor belts and a main control system. The work shows the benefits of coordinated multi-robot setups for automation.
3. **Anon (1985)** – *WABOT-2: Keyboard-playing robot*
One of the first examples of anthropomorphic robots. WABOT-2 was a robot musician able to play a keyboard. It had five subsystems (limb control, vision, conversation, singing voice tracking, and supervisory control), showing the early ambition to copy human perception and action in a service context.
4. **Semjon (2014)** – *Solution collision relations in multirobotic systems*
Focuses on collision avoidance in multi-robot systems using offline simulations. The case study is on welding, where multiple industrial robots need to coordinate.
5. **Galvan-Perez et al. (2020)** – *Kinematic coupling of a mobile manipulation system*
Proposes a model for coupling a 3-DOF manipulator with a mobile robot, also considering wheel slippage. The study shows how mobility combined with manipulation can extend the workspace and improve performance.

4.8.3 Temporal Trends (IMTP per Year)

The evolution of Topic 8, measured through the Index of Mean Topic Proportion (IMTP), shows the following dynamics:

- **Until 1985:** the topic is marginal but not completely absent. A few works show the first attempts to use adaptive methods in robotics, with very low IMTP values.
- **1985–2000:** the first peak happens in the mid-1980s, linked to interest in adaptive learning methods and systems able to improve with experience. After this, the trend stabilizes at a modest level.
- **2005–2015:** a new growth phase starts, supported by reinforcement learning and better computational power. Many experiments are simulations or small tests on physical robots.
- **2016–present:** the topic reaches its highest point. With deep reinforcement learning (like DQN and PPO) and simulators (MuJoCo, OpenAI Gym), research increased a lot. Now humanoids are trained for tasks such as walking, object manipulation, and dynamic interaction.

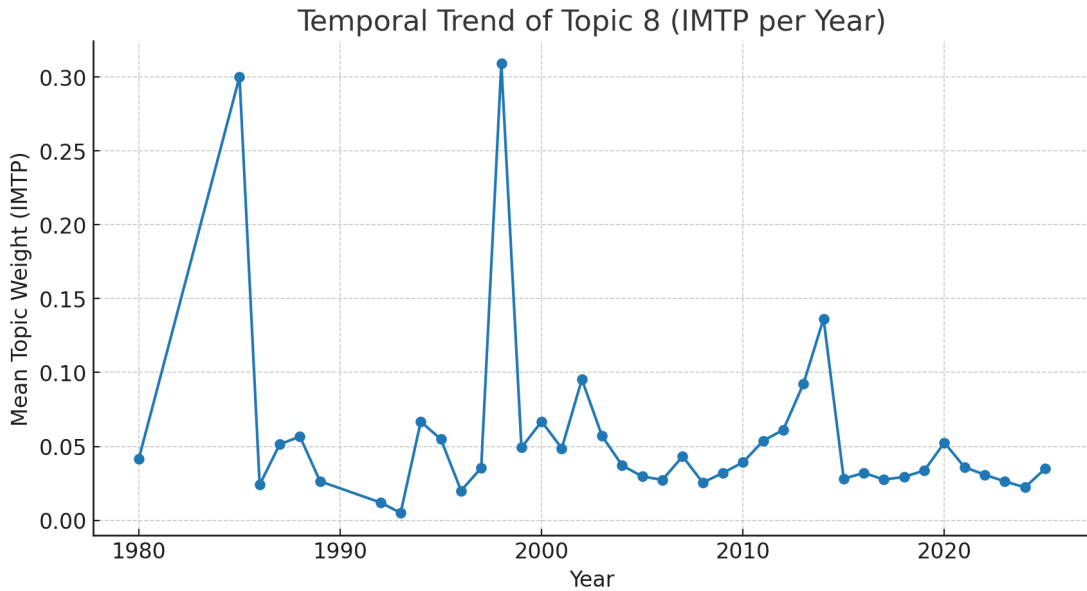


Figure 23: Topic 8: Mobile Manipulation and Reconfigurable Robotic Workstations (IMTP per Year)

Overall, Topic 8 reflects a multi-wave trajectory: a pioneering phase in the 1980s, followed by a long consolidation, and finally a sharp recent boom enabled by deep learning and large-scale simulation.

4.9 Topic 9 - Mechanical Systems Analysis and Simulation in Robotics and Automation

4.9.1 Topic Description

Topic 9 is about the role of robotics, mechatronics, and automation inside industrial and manufacturing systems. Most of the contributions are conference proceedings, where many papers are collected together. These papers cover humanoid robot dynamics, human–robot interaction, industrial automation, control, and simulation methods. The focus is not on single experiments, but on giving a wide overview of technological progress in robotics and mechatronics, showing how robotics is being integrated into larger industrial ecosystems.

4.9.2 Most Relevant Articles

Inside Topic 9, the documents with the highest weight are mostly conference proceedings. This is an effect linked to how Scopus indexes, because in some cases it registers the whole volume of a conference as one bibliographic record. These documents have very large content, since they include dozens of contributions on different themes, and this can create an over-representation in some topics.

For this reason, in the interpretation phase the proceedings were considered only as context evidence, but the qualitative analysis of the topic focused mainly on single contributions (articles and conference papers).

Proceedings with higher weight among the documents with higher weight there are:

1. **MIMT 2012 (2012)** – *3rd International Conference on Mechanical, Industrial and Manufacturing Technologies*

This conference volume includes 56 papers on humanoid robot walking

control, industrial system simulation, and smart cars. It shows the wide variety of robotics applications in manufacturing and engineering.

2. **ICMRA 2013 (2013)** – *International Conference on Mechatronics, Robotics and Automation*

Collects 447 papers, covering humanoid dynamics, service robots, UAV teleoperation, mobile robots, and industrial automation. It reflects the expansion of robotics into many areas and its step-by-step adoption in industry.

3. **IFMATT 2013 (2014)** – *International Forum on Materials Analysis and Testing Technology*

A collection of 319 papers on material science, manufacturing, and robotics. It includes studies on humanoid control, telepresence, and intelligent service robots, showing the link between robotics and advanced manufacturing technologies.

These volumes cannot be read as single contributions, but they confirm how robotics and mechatronics are entering industrial and production chains, with a focus on modelling, control, and simulation methods.

Among the single contributions with relevant weight, the following three stand out:

1. **Havlík et al. (2006)** - *Research in robotics and human medical rehabilitation.*

This paper shows an interdisciplinary approach that combines the design of industrial and humanoid robots with knowledge about the human body for medical rehabilitation. It talks about using computer modelling, simulation, visualization, and FEM analysis to improve both robotic systems and rehab methods.

2. **Latif et al. (2017)** - *Volumetric flow visualization system using CW laser & scanning mirrors.*

This work presents a system for 3D visualization of flows using continuous wave lasers and scanning mirrors. The system creates uniform light intensity and multi-layer laser sheets to generate 3D flow images. It can be applied in areas like aerospace, robotics, and precision engineering.

3. **Du et al (2025)** - *Theoretical and experimental investigation of the differential planetary roller screw mechanism condition monitoring and public dataset.*

The study proposes a test rig to monitor differential planetary roller screws (DPRS) in extreme conditions. It combines mechanical modelling with advanced signal processing and neural networks. The paper also validates the method with experiments and provides a public dataset for future research.

4.9.3 Temporal Trends (IMTP per Year)

- **Until 1990:** the topic is almost absent, with very few early works, more about human biomechanics than robots.
- **1990–2005:** first growth, driven by interest in modelling human gait and applying these ideas to humanoids. Kinematic and dynamic models were used to study stability, posture, and energy consumption.
- **2005–2015:** a consolidation phase, with systematic studies on locomotion and biomechanical models for robotic limbs and joints. Early humanoid prototypes started to walk more naturally, often compared with human gait.
- **2016–present:** the topic reaches its maturity. IMTP values grow and stay high, showing strong interest. Applications include robotic rehabilitation and humanoids able to adapt to complex terrains. Biomechanical models are no longer only theory, but design standards to improve motor control, energy efficiency, and physical interaction with humans.
- for improving motor control, energy efficiency, and human–robot physical interaction.

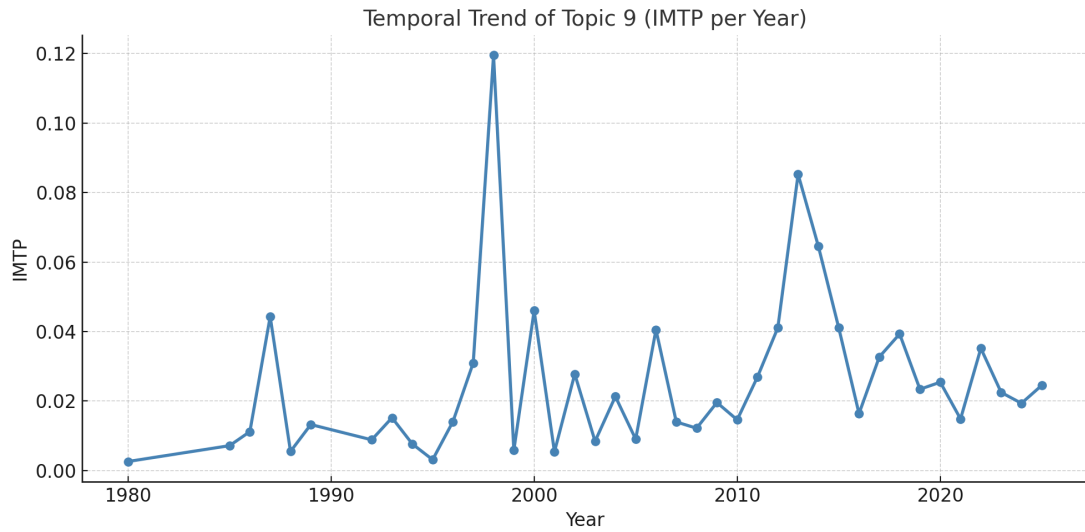


Figure 24: Topic 9: Mechanical Systems Analysis and Simulation in Robotics and Automation (IMTP per Year)

Topic 9 highlights a clear path: from early theoretical studies in the 1990s to today’s widespread use of biomechanics as a cornerstone in humanoid robot design and validation.

4.10 Topic 10 - Human-Robot Interaction, Intelligent Agents and Immersive Technologies

4.10.1 Topic Description

This topic focuses on the interaction between humans and intelligent systems, with focus on humanoid robots, conversational agents and immersive technologies. It shows how AI agents and robotic platforms can help human-machine collaboration in different contexts, like education, training, entertainment and digital platforms. The main themes are trust in AI, cognitive models of agents, and the design of immersive interaction experiences.

4.10.2 Most Relevant Articles

As already seen in Topic 9, also in Topic 10 the documents with the highest weight are mostly conference proceedings. This happens because of the way Scopus indexing works: sometimes a whole conference volume is recorded as one single bibliographic entry, which increases its relative weight in the model. For this reason, the proceedings

were used only as contextual evidence, while the qualitative analysis focused on single contributions, like articles and conference papers.

Proceedings with higher weight among the documents with higher weight there are:

- *25th IFIP WG 5.5 Working Conference on Virtual Enterprises, PRO-VE 2024* (Conference review, IFIP Advances in Information and Communication Technology). This volume collects 56 contributions about human-machine collaboration, human-robot interaction, collaborative artificial intelligence and immersive technologies.
- *3rd International Conference on Entertainment Computing, ICEC 2004* (Lecture Notes in Computer Science). This volume includes 82 contributions, some of them about motion capture and applications of humanoid robots in entertainment.
- *International Conference on Autonomous Agents 2000*. This volume has more than one hundred papers on autonomous robotics, software agents and multi-agent communication, with some sections about humanoid robots and human-machine collaboration.

These documents, even if they cannot be seen as single contributions, show that the topic is strongly connected to the interaction between humans and complex artificial systems (humanoid robots, intelligent agents, collaborative and immersive environments).

Articles and single contributions among the following documents with relevant weight, that are the main base of the qualitative analysis, there are:

1. **Zhao et al. (2024)** - *Conformal Neuromorphic Bioelectronics for Sense Digitalization (Advanced Materials)*. The article explores neuromorphic bioelectronic devices for sense digitalization, with applications in soft robotics and human-machine interfaces, including possible uses in humanoid robots and cybernetic systems.
2. **Treur & Umair (2012)** - *A human-like agent model for attribution of actions using ownership states and inverse mirroring (Lecture Notes in*

Artificial Intelligence). This paper presents a cognitive model inspired by neurological processes to explain how artificial agents can attribute actions to themselves and to others, with potential applications in human-robot interaction and virtual agents.

3. **Lin, Lee & Lu (2024)** - *Embodied AI with Large Language Models: A Survey and New HRI Framework (ICARM 2024)*. This work proposes a framework for human-robot interaction based on embodied AI and large language models (LLM), with the goal to improve the capacity of social robots to create personalized connections with users.

4.10.3 Temporal Trends (IMTP per Year)

The evolution of Topic 10, measured via the Index of Mean Topic Proportion (IMTP), highlights the following dynamics:

- **Until 1995:** almost no production, because computer vision was still very new and not connected to humanoid robots.
- **1995–2005:** the first works appear, linking vision algorithms like shape recognition and motion tracking to navigation and control. These studies were mostly experimental, with small datasets and limited sensors.
- **2005–2015:** a strong growth phase, thanks to RGB-D cameras (like Kinect) and more robust recognition algorithms. Robots started to see objects and environments in a more realistic way, improving interaction and manipulation.
- **2016–present:** the topic reaches full maturity with deep learning, that changed visual perception completely. Recent studies combine convolutional neural networks with multimodal sensing, so humanoids can now recognize faces, gestures, objects, and even understand complex scenes. The stable IMTP growth shows that vision has become a key element for humanoid cognitive and social skills.

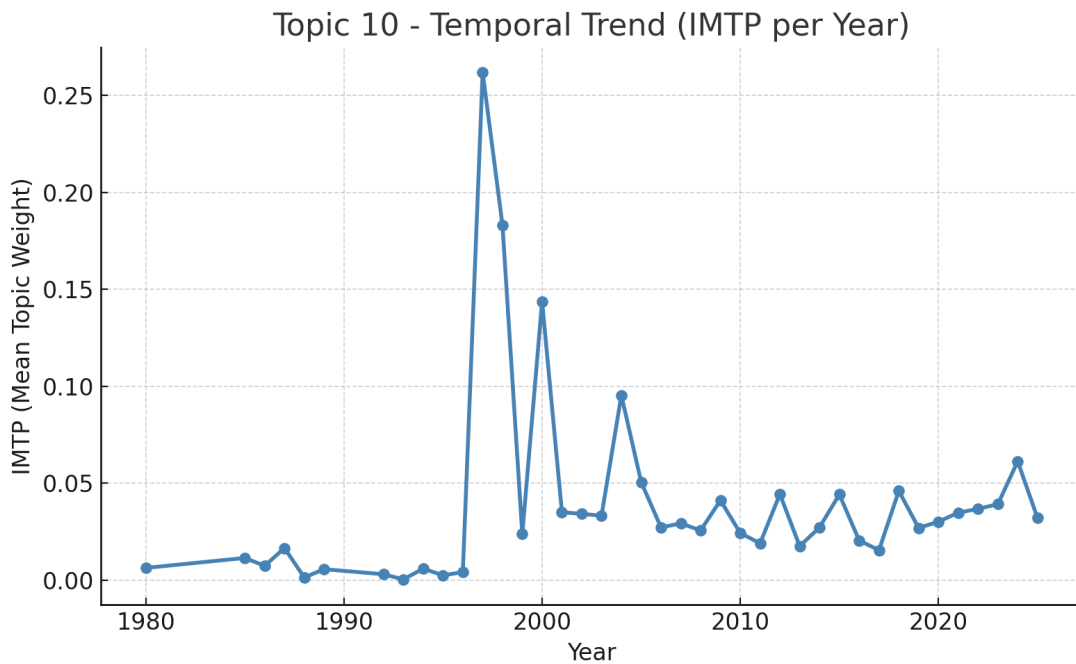


Figure 25: Topic 10: Human-Robot Interaction, Intelligent Agents and Immersive Technologies (IMTP per Year)

Overall, Topic 10 illustrates the transition from early, rudimentary vision algorithms to advanced AI-driven perception systems that allow humanoids to operate and interact in complex real-world environments.

4.11 Topic 11 - Kinematics and Stiffness Optimization of Anthropomorphic Robot Arms

4.11.1 Topic Description

This topic looks at kinematic modelling, optimization, and stiffness analysis of anthropomorphic and humanoid robot arms. The focus is on forward and inverse kinematics, workspace analysis, and redundancy resolution, using both closed-form and optimization methods. A common point in these works is the attempt to copy the dexterity of the human arm, making robots more flexible, stable, and precise in their movements. The studies are not only about theory and equations but also include simulations and applications for industrial and service robots.

4.11.2 Most Relevant Articles

Based on topic weights, the five most influential publications are:

1. **Chen et al. (2013)** – *Stiffness analysis and optimization of a novel cable-driven anthropomorphic-arm manipulator*
Analyses the Cartesian stiffness of a 7-DOF hybrid cable-driven manipulator. The study introduces a stiffness optimal algorithm to improve stability during motion, tested and confirmed with simulations.
2. **Bajd et al. (2013)** – *Geometric model of anthropomorphic robot with spherical wrist*
Presents forward and inverse kinematic models for a 6-DOF industrial robot with a spherical wrist. The paper focuses on how to calculate joint displacements and poses, giving a good base for robot motion planning.
3. **Song & Wang (1988)** – *Effect of nonzero end-effector angle on manipulator dexterous workspaces*
Explores how different end-effector angles affect workspace dexterity. Using geometry sweeping methods, the study shows that a 90° angle gives the best dexterity, taking inspiration from how humans grasp objects.
4. **Cui et al. (2010)** – *Kinematics analysis and simulation of a 6-DOF humanoid robot manipulator*
Uses Denavit–Hartenberg parameters and transformations to get forward and inverse kinematics for a humanoid manipulator. The results are validated with simulations, offering useful tools for humanoid robot control.
5. **Pfurner (2016)** – *Closed form inverse kinematics solution for a redundant anthropomorphic robot arm*
Develops a closed-form solution for the inverse kinematics of a 7R redundant anthropomorphic arm. The method avoids iterative calculations and can be used for singularity avoidance and optimization of joint movements.

4.11.3 Temporal Trends (IMTP per Year)

The temporal evolution of Topic 11, based on the IMTP, can be summarized as follows:

- **Until early 2000s:** very few works. Learning in robots was studied mostly with theory and simulations, without real applications.
- **2005–2015:** strong growth phase. Reinforcement learning and neural networks started being used for locomotion, manipulation, and social interaction. Robots began to adapt to their environment, either with trial-and-error or by imitating humans.
- **2016–present:** the topic becomes central. With deep learning and transfer learning, humanoids can now generalize from one task to another. Recent studies show robots that can grasp new objects, coordinate with other agents, or personalize interactions with users. The high and stable IMTP values show that AI-driven adaptation is no longer experimental but a structural part of humanoid robotics.

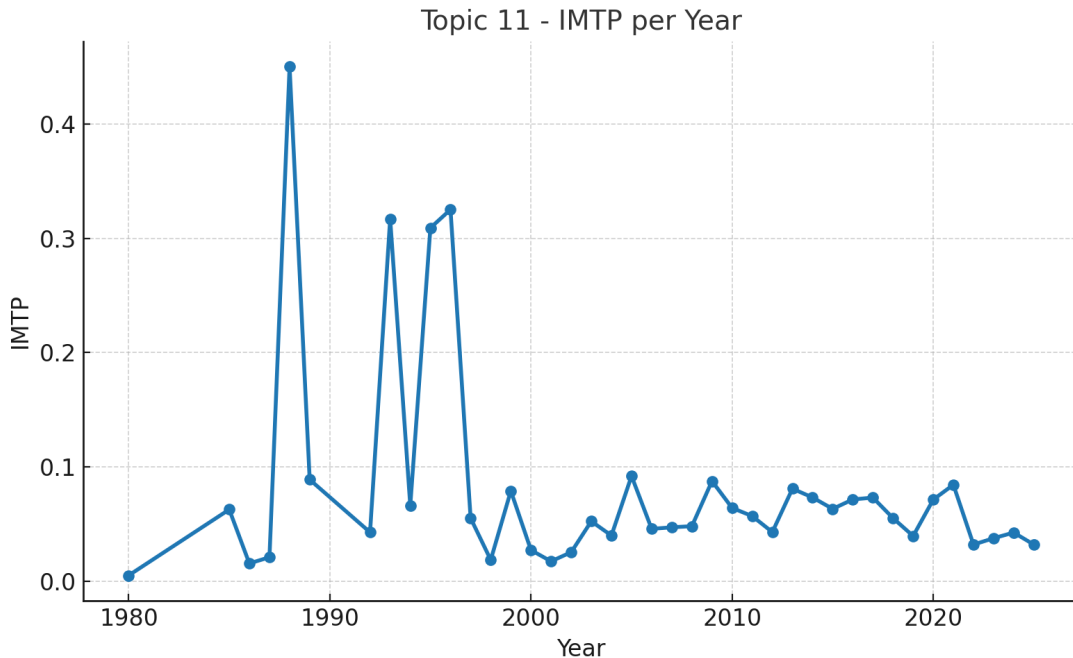


Figure 26: Topic 11: Kinematics and Stiffness Optimization of Anthropomorphic Robot Arms (IMTP per Year)

In short, Topic 11 illustrates the shift from theoretical approaches to practical, adaptive systems, confirming its strategic role in advancing humanoids toward autonomy, flexibility, and human-like behaviour.

4.12 Topic 12 - Trajectory Generation and Task Execution in Humanoid Robots

4.12.1 Topic Description

This topic focuses on methods that enable humanoid robots to imitate human movements, execute complex tasks, and plan trajectories in dynamic environments. Research ranges from motion capture analysis and dance archiving, to the development of multitasking programming architectures and optimization-based algorithms for real-time motion planning and dual-arm manipulation.

4.12.2 Most Relevant Articles

Based on topic weights, the five most influential publications are:

1. **Suleiman W. (2008)** - *On human motion imitation by humanoid robot*, presents an optimization-based approach to allow humanoid robots to imitate human-captured motions. The imitation problem is formulated as a constrained optimization task, considering the robot's physical limitations, and solved with a recursive dynamics algorithm for efficient gradient calculation.
2. **Shiratori T. (2003)** - *Rhythmic motion analysis using motion capture and musical information*, proposes an archiving method for traditional Japanese dance patterns, integrating music rhythm into motion primitives. This ensures that the reproduced motions are synchronized with the rhythm, resulting in more natural and realistic humanoid robot performances.
3. **Han J. (2013)** - *A multitasking architecture for humanoid robot programming*, introduces a three-tier programming architecture for humanoid robots, combining motion primitives with an extended motion description

language. The system enables prioritized coordination of multiple tasks while accounting for physical and dynamic constraints.

4. **Shao J. (2024)** - *Online Trajectory Generation With Local Replanning for 7-DoF Serial Manipulator*, proposes a real-time trajectory planning method for anthropomorphic manipulators. By leveraging an analytical inverse kinematics solution, the framework allows efficient collision avoidance and online replanning in dynamic environments.
5. **Qin Y. (2023)** - *Dual-Arm Mobile Manipulation Planning of a Long Deformable Object*, develops a hierarchical planner for manipulating deformable objects with dual-arm humanoid robots. The method integrates regrasp strategies, mobility, and obstacle constraints, validated experimentally in industrial scenarios.

4.12.3 Temporal Trends (IMTP per Year)

- **1990s – early 2000s:** almost no contributions. Visual capabilities were limited to very simple recognition algorithms, often tested only in controlled environments.
- **2005–2015:** steady growth phase. New methods for feature detection and object recognition made it possible to improve navigation, obstacle detection, and basic object interaction. Some works also used stereo perception and multi-sensor fusion to get a better understanding of the scene.
- **2016–present:** the trend becomes stable with high IMTP values. This matches the rise of deep learning in computer vision: convolutional networks and semantic segmentation allow humanoids to recognize complex environments, faces, and even human actions. Recent studies show practical uses like gesture recognition for human-robot interaction or real-time perception for autonomous walking.

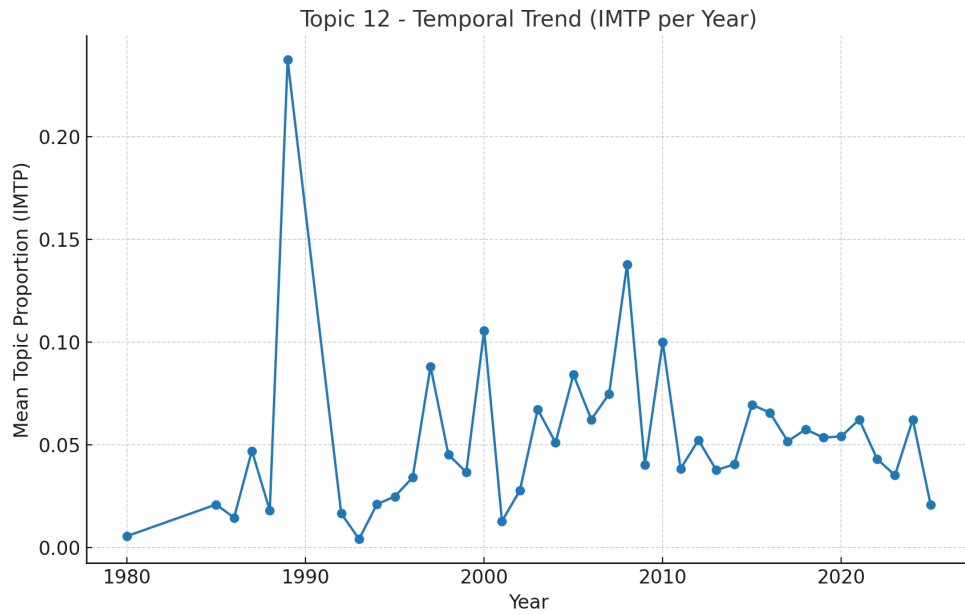


Figure 27: Topic 12: Trajectory Generation and Task Execution in Humanoid Robots (IMTP per Year)

Topic 12 marks the evolution from basic vision algorithms to advanced AI-powered perception, making it a core pillar for humanoid autonomy and intelligence.

4.13 Topic 13 - Design and Functionality of Robotic Hands for Dexterous Manipulation

4.13.1 Topic Description

This topic is about the design and optimization of under-actuated and self-adaptive robotic hands. The papers focus on new mechanical solutions, like tendon-slider or gear rack systems, to make grasping more stable, adaptable, and dexterous, but also simple and not too expensive. The research shows the importance of finding a balance between a human-like shape and practical use, with the goal of giving humanoid robots hands that can be as versatile as the human ones.

4.13.2 Most Relevant Articles

Based on topic weights, the five most influential publications are:

1. **Sun & Zhang (2012)** – *A novel coupled and self-adaptive under-actuated multi-fingered hand with gearrack-slider mechanism.*
Introduces the COSA-GRS hand, which combines coupled and self-adaptive grasping using a gearrack-slider system. It allows both pre-shaping and adaptive grasping, reaching good stability and human-like dexterity.
2. **Che & Zhang (2011)** – *A dexterous and self-adaptive humanoid robot hand: GCUA hand.*
Presents the GCUA hand, designed with a pulley-belt mechanism. It can change gestures, gives stable grasps, and reduces control difficulties. The work shows a balance between dexterous and simpler under-actuated hands.
3. **Zhang et al. (2009)** – *A dexterous and self-adaptive humanoid robot hand: Gesture-changeable under-actuated hand.*
An earlier work about the GCUA hand idea. It shows how gesture-changeable under-actuation can improve adaptability and grasping stability, preparing the way for later improvements.
4. **Jin et al. (2012)** – *LISA Hand: Indirect self-adaptive robotic hand for robust grasping and simplicity.*
Proposes the LISA hand, based on block-linkage-slot mechanisms with very few motors. It keeps the design simple and cheap, but still robust and adaptive for grasping.
5. **Wang et al. (2009)** – *The indirect style under-actuated robotic finger with tendon-slider mechanisms.*
Develops the tendon-slider finger, used in the TH-2T hand. This mechanism reduces costs and structure complexity, while making the hand more adaptable to different object shapes.

4.13.3 Temporal Trends (IMTP per Year)

The evolution of Topic 13, measured via the Index of Mean Topic Proportion (IMTP), highlights the following dynamics:

- **1990s – early 2000s:** almost no works, with IMTP values close to zero. At this time, speech interaction was very basic, with rigid and command-based systems.
- **2005–2015:** strong growth phase. The first humanoids with integrated speech recognition appear. Research focused on multilingual recognition, robustness to noise, and statistical models like HMMs. Some studies also worked on more natural speech, with generation synchronized to facial expressions.
- **2016–present:** consolidation with high IMTP values. Deep learning dominates, giving more accurate recognition and natural speech synthesis. Humanoids can now understand natural language, manage multi-turn conversations, and adapt to context. Applications in education, healthcare, and social environments show how central speech has become in human-robot interaction.

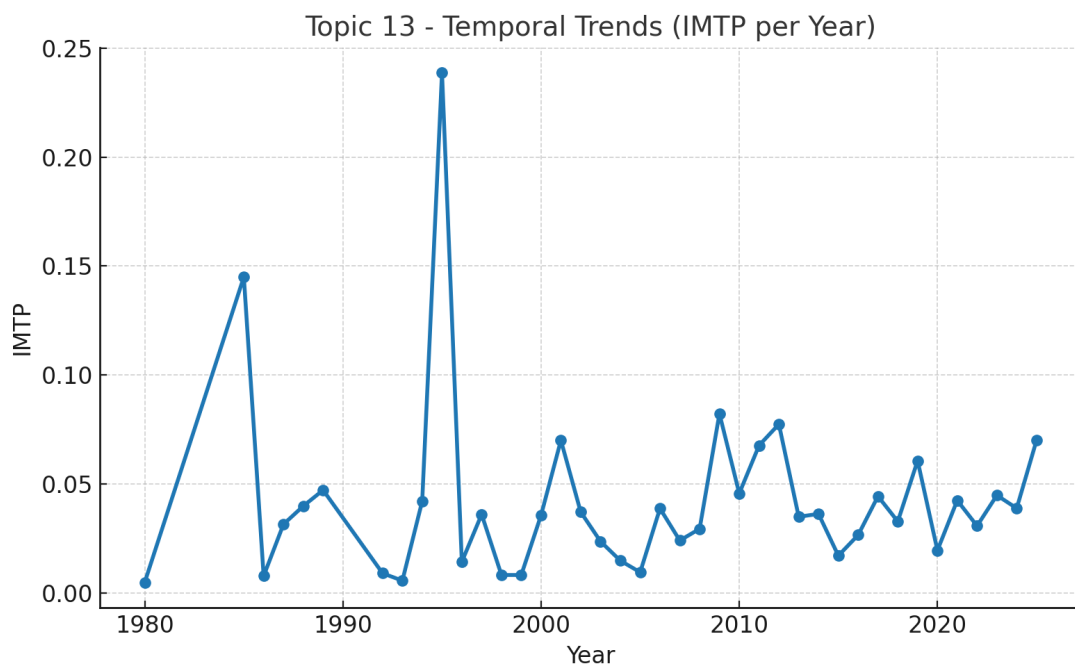


Figure 28: Topic 13: Design and Functionality of Robotic Hands for Dexterous Manipulation (IMTP per Year)

Topic 13 illustrates the transition from rigid command-based speech to natural, adaptive dialogue, establishing language as a key enabler of social humanoids.

4.14 Topic 14 - Dynamic Locomotion and Stability Control in Humanoid Robots

4.14.1 Topic Description

This topic looks at how humanoid robots can walk, shuffle, jump, and recover balance in dynamic situations. The focus is on locomotion and stability control, with methods that improve motion and help robots stay stable when they face disturbances or work in tight spaces. Research includes both classical models, like inverted pendulum walking pattern generation, and more recent ideas, such as whole-body capturability and partition-aware control. The trend shows a move from simple models to more complete approaches that combine biomechanics, dynamics, and control to make humanoid locomotion more stable and reliable.

4.14.2 Most Relevant Articles

Based on topic weights, the five most influential publications are:

1. **Hong et al. (2008)** — *Walking pattern generation for humanoid robots with LQR and feedforward control method.* Presents a walking pattern method that uses an inverted pendulum model with feedforward pole-zero cancellation and LQR feedback. This hybrid approach solves non-minimum phase problems and improves trajectory tracking.
2. **Nemoto et al. (2015)** — *Rolling Locomotion Control of a Biologically Inspired Quadruped Robot Based on Energy Compensation.* Introduces a quadruped robot inspired by biology that can switch between walking and rolling. The energy-compensation controller ensures stable and periodic rolling motions.
3. **Lu et al. (2024)** — *Trajectory Planning for Jumping and Soft Landing With a New Wheeled Bipedal Robot.* Proposes trajectory planning for jumping and soft landing in a wheeled bipedal robot. Using virtual model control and force compensation, the robot can jump with precision and reduce impact when landing.

4. **Kojima et al. (2015)** — *Shuffle motion for humanoid robot by sole load distribution and foot force control.*
Focuses on shuffle motion in constrained factory spaces. The authors propose Slide Friction Control (offline) and Slide Contact Stabilizer (online) to keep balanced load distribution and smooth sliding motions.
5. **Song et al. (2024)** — *Partition-Aware Stability Control for Humanoid Robot Push Recovery With Whole-Body Capturability.*
Develops a partition-aware stability control for push recovery, using whole-body capturability in the augmented COM state space. By including nonlinear dynamics and kinematic limits, the method performs better than reduced-order models in keeping balance after perturbations.

4.14.3 Temporal Trends (IMTP per Year)

The evolution of Topic 14, measured via the Index of Mean Topic Proportion (IMTP), shows the following trajectory:

- **1980–1995:** only a few works, with very low IMTP values. These were pioneering studies, far from today’s humanoid context.
- **000–2010:** clear growth, thanks to the spread of digital cameras and the first algorithms for object recognition and motion tracking. Humanoids began to use vision for navigation and object or face recognition.
- **2015–present:** consolidation at high levels. Deep learning and convolutional neural networks boosted visual perception, making humanoids able to understand complex scenes, emotions, and link vision with motor control. The high and stable IMTP values show that vision is now a key and permanent part of humanoid robots.

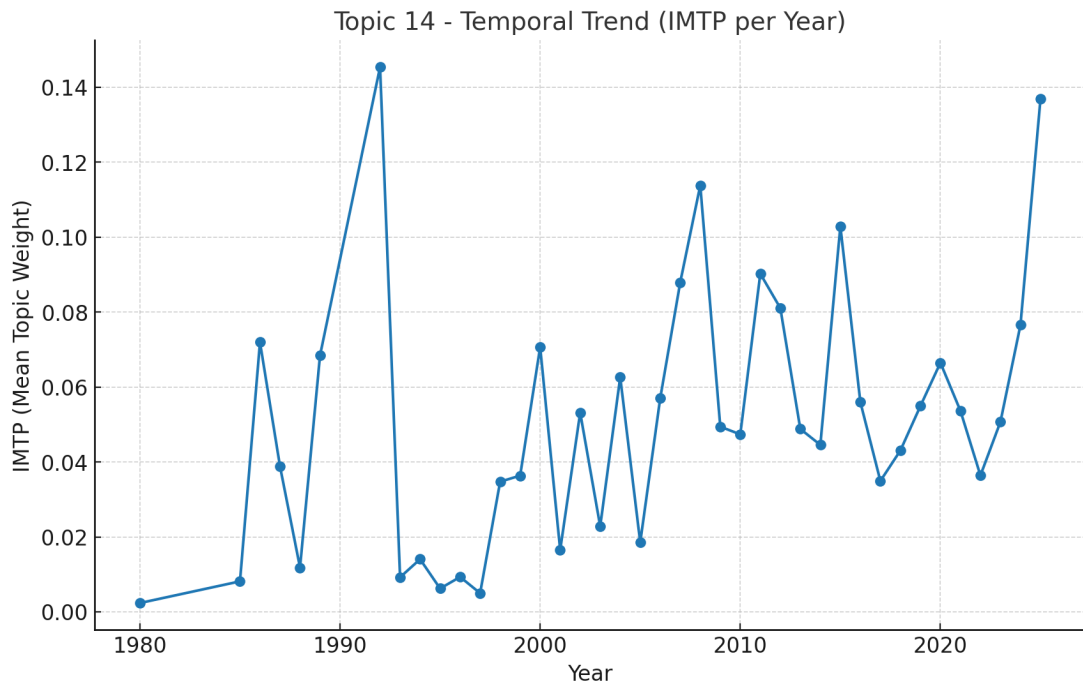


Figure 29: Topic 14: Dynamic Locomotion and Stability Control in Humanoid Robots (IMTP per Year)

Taken together, Topic 14 highlights the evolution of vision from a niche experiment to a core capability driving humanoid perception and cognition.

4.15 Topic 15 - Visual Sensing and Object Localization in Humanoid and Mobile Robotics

4.15.1 Topic Description

This topic studies visual sensing and object localization in humanoid and mobile robots. The research looks at methods for 3D pose estimation, mapping of environments, and sensor fusion to help robots work in unstructured spaces. Techniques include laser scanning, point cloud processing, and deep learning frameworks for vision, all aimed at making localization more accurate and robust. An important point is the shift from classical geometric models to learning-based methods, which allow humanoids to do harder tasks such as climbing, navigation, and manipulation with more autonomy.

4.15.2 Most Relevant Articles

Based on topic weights, the five most influential publications are:

1. **Chen et al. (2015)** — *3D model-based ladder tracking using vision and laser point cloud data*. Presents a 3D ladder tracking system for the ATLAS robot during the DARPA Robotics Challenge. The method combines vision with laser point cloud data, using virtual visual servoing and iterative closest point algorithms for reliable pose estimation and recovery.
2. **Fabris et al. (2020)** — *3DOPE-DL: Accuracy Evaluation of a Deep Learning Framework for 3D Object Pose Estimation*. Evaluates Dense Fusion, a deep learning framework for 3D object pose estimation. The paper also introduces a new ISS dataset with RGB-D cameras and anthropomorphic robots, and provides a detailed analysis of accuracy and uncertainty.
3. **Park et al. (2011)** — *Ground height map generation for a humanoid robot in an unstructured environment*. Proposes a system that uses a laser scanner on a humanoid robot to create ground height maps in unstructured environments. The method extracts 3D depth maps and applies plane segmentation, making navigation more reliable.
4. **Han et al. (2024)** — *PoseFusion: Multi-Scale Keypoint Correspondence for Monocular Camera-to-Robot Pose Estimation in Robotic Manipulation*. Introduces PoseFusion, a framework that improves monocular pose estimation with multi-scale keypoint correspondence and residual refinement. The system helps improve calibration and robustness for robot manipulation.
5. **Liu et al. (2019)** — *Accelerating DNN-based 3D point cloud processing for mobile computing*. Presents a hardware accelerator for deep neural networks used to

process 3D point cloud data in mobile robots. The design improves speed and energy efficiency compared to GPU-based solutions.

4.15.3 Temporal Trends (IMTP per Year)

The evolution of Topic 15, measured via the Index of Mean Topic Proportion (IMTP), shows the following dynamics:

- **1980s–2000:** the topic was almost absent, with IMTP close to zero and no major research.
- **2010–2015:** first works appeared, focused on pneumatic fibre-reinforced actuators and bio-inspired materials, creating the base for soft robotics.
- **2015–2020:** steady growth, with applications like soft grippers for delicate manipulation and safer human–robot interfaces.
- **2020–today:** further consolidation, supported by 3D-printed elastomers, biomedical robotics (like robotic endoscopy), and wearable devices.

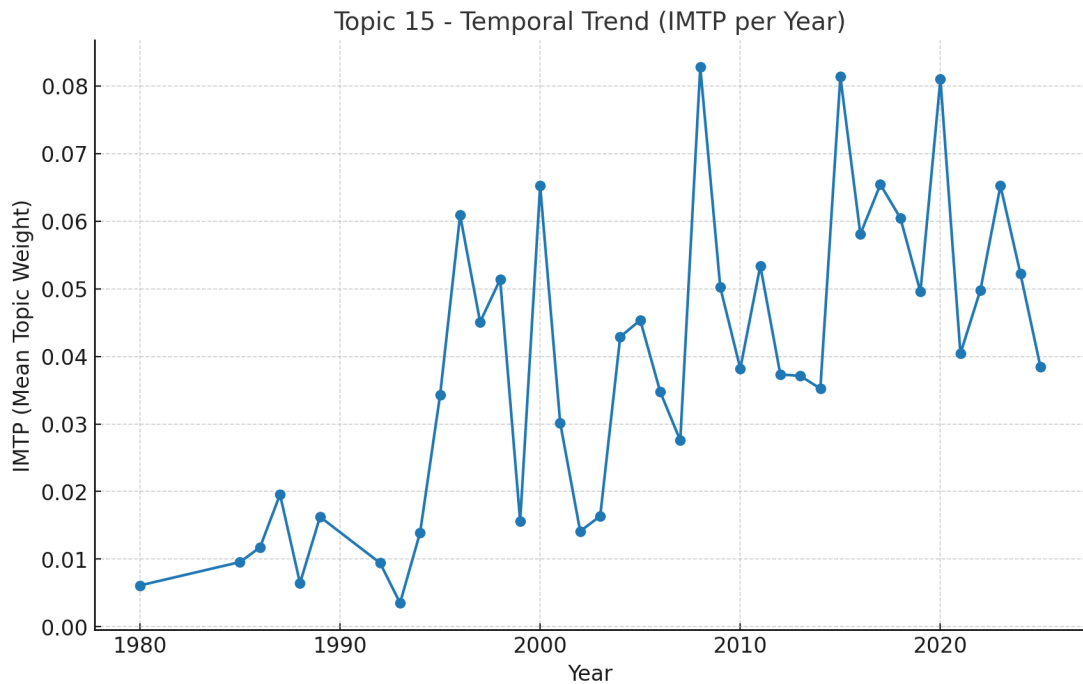


Figure 30: Topic 15: Visual Sensing and Object Localization in Humanoid and Mobile Robotics (IMTP per Year)

In short, the graph highlights how soft robotics evolved from a marginal topic to a central research field, powered by technological advances that enabled real and increasingly widespread applications.

4.16 Topic 16 - Robotic Additive Manufacturing and Process Monitoring

4.16.1 Topic Description

This topic studies robotic additive manufacturing (AM) and process monitoring. Research looks at in-situ sensing, like laser triangulation and coaxial cameras, together with closed-loop control and online re-slicing to keep deposition geometry stable and fix problems such as shrinkage or height drift. Other works show robotized extrusion and filament winding for large and complex parts, with anthropomorphic robot arms used as flexible AM platforms. These robots make it possible to extend build volume and allow multi-directional deposition.

4.16.2 Most Relevant Articles

1. **Donadello et al. (2019)** - *Monitoring of laser metal deposition height by means of coaxial laser triangulation.*
Presents coaxial laser triangulation in an LMD head for real-time height monitoring. It reconstructs spatial height maps and shows self-regulating layer thickness behaviour.
2. **Donadello et al. (2018)** - *Coaxial laser triangulation for height monitoring in laser metal deposition.*
An early demo of coaxial triangulation on a robot-mounted fibre-laser LMD system. The method allows direction-independent measurement over millimetre ranges.
3. **Rebaioli et al. (2019)** - *A solution to manufacture structural parts with concave surfaces by robotized filament winding.*
Shows robotized screw-extrusion AM for large plastic parts, with closed-loop Z correction and online re-slicing to keep target height. It reaches up to 1250 cm³/h flow, with the robot's workspace as the only limit.
4. **Magnoni et al. (2017)** - *Robotic AM System for Plastic Materials: Tuning and On-line Adjustment of Process Parameters.*
Presents an industrial screw-based extruder on an anthropomorphic robot. Parameters are tuned with DoE, and online adjustments are made from deposition data to regularize bead geometry.
5. **Anamateros et al. (2007)** - *Process parameters tuning and online re-slicing for robotized additive manufacturing of big plastic objects.*
Proposes robotized filament winding with synchronized pneumatic devices to avoid fibre bridging on concave surfaces. The paper shows how process parameters affect the final composite strength.

4.16.3 Temporal Trends (IMTP per Year)

- **1980–1990:** the first articles appear, with isolated signals in 1986 and 1989, but this is not yet stable research. They look more like pioneering trials than a trend.
- **1991–2000:** 1993 and 1994 show unusual peaks, probably from a few influential papers. After that, values drop again and the topic is not yet solid.
- **2001–2010:** a clearer growth phase begins. From 2006 onwards, average weights stabilize at higher levels, showing that research became more continuous and structured.
- **2011–2020:** the strongest phase of consolidation. Peaks appear in 2013–2014 and especially 2019, when IMTP values reach their maximum. The rise of additive manufacturing and better control systems in robotics are the main drivers.
- **2021–2025:** values stay high but fluctuate more. After a dip in 2020, there are rebounds up to 2022, even if not back to 2019 levels. Interest remains strong, but growth is no longer as fast.

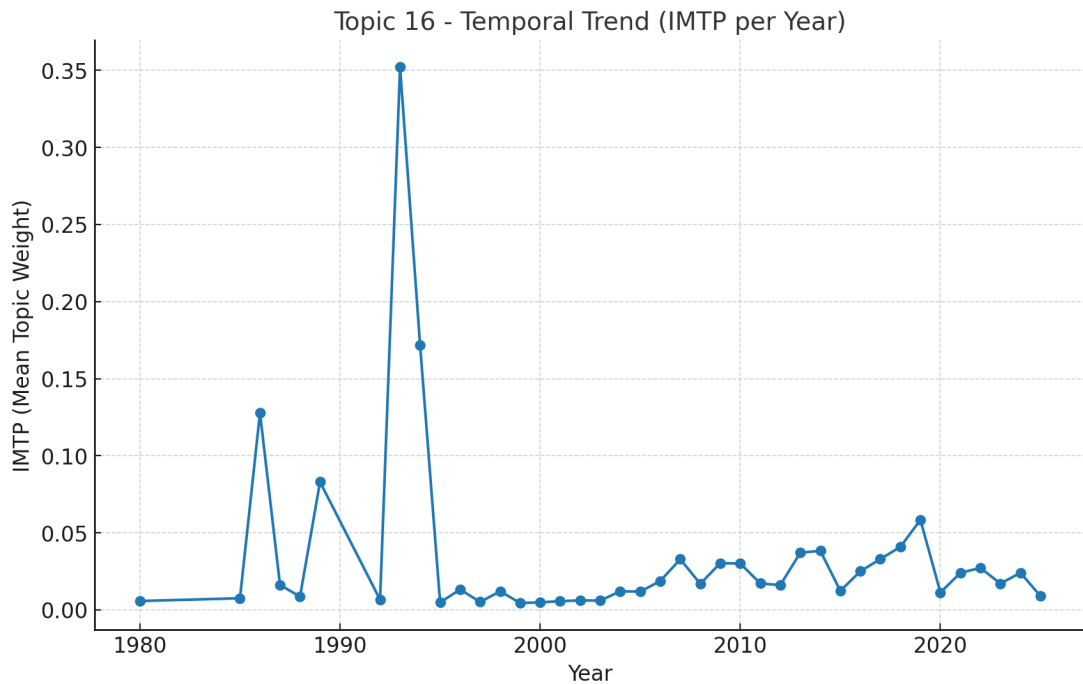


Figure 31: Topic 16: Robotic Additive Manufacturing and Process Monitoring (IMTP per Year)

Taken together, Topic 16 illustrates the transition from early composite winding solutions to advanced robotized AM systems with embedded monitoring and adaptive control, emphasizing scalability, flexibility, and quality assurance in large-part manufacturing.

4.17 Topic 17 - Emotion Recognition and Expression in Humanoid Robot Interaction

4.17.1 Topic Description

This topic looks at emotion recognition and expression in humanoid robot interaction. Research includes computational models of affect, like need models, equations of emotion, and Plutchik's theories. It also studies speech interaction with lip synchronization and even hardware solutions such as memristive circuits for brain-like emotional learning. The idea is to give humanoid robots the ability to recognize, generate, and adapt emotional states, so they can communicate more naturally, be socially accepted, and act as companions.

4.17.2 Most Relevant Articles

1. **Wang et al. (2023)** — *Memristive Circuit Design of Brain-Like Emotional Learning and Generation*
Proposes a memristive circuit inspired by the limbic system for emotional learning and generation. The system mimics neurons and synapses to create continuous emotions in a 2D valence–arousal space, opening new paths for personalized emotional interaction in humanoid robots.
2. **Miwa et al. (2003)** — *Introduction of the Need Model for Humanoid Robots to Generate Active Behavior*
Introduces the Need Model in the humanoid WE-4R. Needs like security, appetite, and exploration drive behaviours, allowing robots to act and express internal motivations in a human-like way.
3. **Luo et al. (2011)** — *Human robot interactions using speech synthesis and recognition with lip synchronization*
Presents a system for speech synthesis and recognition with lip synchronization to make human–robot communication more natural. Combining auditory and visual signals improves user perception of closeness and realism.
4. **Vircikova et al. (2013)** — *Personalized emotional expressions to improve natural human-humanoid interaction*
Explores personalized emotional expressions using the Nao humanoid robot. Emotions are generated through fuzzy logic combining human inputs, making the robot able to evolve and adapt its behaviour during interaction.
5. **Miwa et al. (2001)** — *Robot personality based on the equations of emotion defined in the 3D mental space*
Presents the Equations of Emotion model in a 3D mental space (pleasantness, activation, certainty). Robots using this model can simulate personality traits by tuning sensing and expression parameters.

4.17.3 Temporal Trends (IMTP per Year)

- **1980–1990:** the topic appears early, with some spikes like in 1987, but these are isolated and not continuous.
- **1995–2005:** real consolidation phase. Peaks in 1997, 2001, and 2004 show strong activity around additive manufacturing and first robotic applications in complex processes.
- **2010–2015:** another growth phase, with a key peak in 2011, linked to research on advanced process control and modelling.
- **2016–2020:** the topic stays relevant, but with less explosive growth. Research spreads across the literature, focusing more on sensors and process optimization in AM.

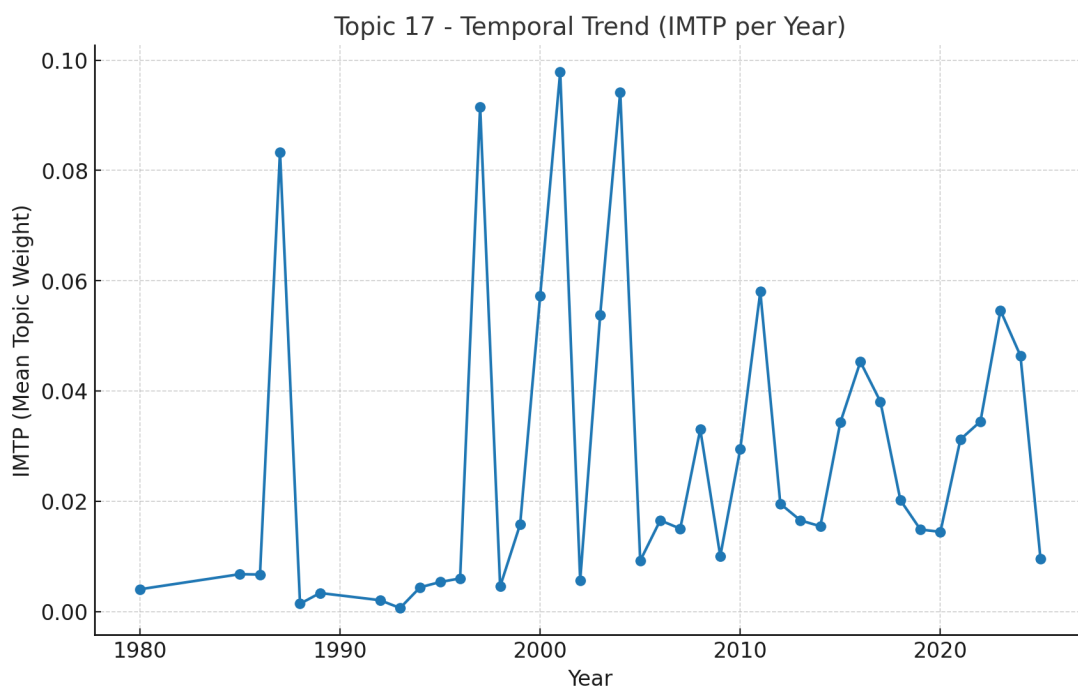


Figure 32: Topic 17: Emotion Recognition and Expression in Humanoid Robot Interaction (IMTP per Year)

Topic 17 doesn't follow a smooth growth curve but instead shows strong peaks at specific times—mainly in the late 1990s and early 2000s. This pattern suggests it is not a continuously emerging field, but one that resurfaces in bursts when new technological pushes occur.

4.18 Topic 18 - Navigation and Task Allocation in Heterogeneous Humanoid Robot Teams

4.18.1 Topic Description

This topic looks at navigation, task allocation, and coordination in heterogeneous humanoid and multi-robot teams. The main idea is how to make robots with different abilities work together safely and efficiently in complex environments. Research covers problems like optimal task allocation when there are limits (for example battery life), dividing complex tasks among multiple robots, navigation in cluttered terrains, and planning safe trajectories for different targets. Other studies explore how robots can collaborate using frameworks such as behaviour trees, optimization methods, or hybrid controllers. In general, the topic shows the move from single-robot navigation to multi-robot coordination systems designed for real industrial and service scenarios.

4.18.2 Most Relevant Articles

Based on topic weights, the five most influential publications are:

1. **Calvo & Capitán (2024)** — *Optimal Task Allocation for Heterogeneous Multi-robot Teams with Battery Constraints*
Presents a MILP-based method for optimal task allocation in heterogeneous robot teams. The approach allows task decomposition, coalition work, and considers recharging, showing the complexity of large-scale coordination.
2. **Coffey & Pierson (2024)** — *Assessing Reputation to Improve Team Performance in Heterogeneous Multi-Robot Coverage*
Introduces a reputation system for multi-robot coverage. By adapting Voronoi partitions based on each robot's past performance, the method improves efficiency and adaptability in persistent coverage tasks.
3. **Heppner et al. (2024)** — *Behavior Tree Capabilities for Dynamic Multi-Robot Task Allocation with Heterogeneous Robot Teams*

Develops a behaviour tree framework for dynamic task allocation. Missions can be defined intuitively by users, and runtime auctions assign tasks to the best robot, improving robustness and execution quality.

4. **Kashyap et al. (2021)** — *Safe Navigation of Humanoid Robot in Cluttered Terrain Using Ant Lion Optimizer Tuned RA Approach*
Proposes a safe navigation method for humanoid robots in cluttered terrains, using Ant Lion Optimizer tuned with regression analysis. Validated in both simulations and real NAO robot experiments, the method improves travel length and computation time.
5. **Kumar Kashyap & Parhi (2021)** — *Multi-objective trajectory planning of humanoid robot using hybrid controller for multi-target problem in complex terrain*
Presents a hybrid controller that combines regression analysis with Improved Spider Monkey Optimization. It optimizes path length, time, and energy consumption, with real experiments confirming better robustness and efficiency.

4.18.3 Temporal Trends (IMTP per Year)

The evolution of Topic 18, measured via the Index of Mean Topic Proportion (IMTP), highlights the following dynamics:

- **1990–1995:** first peak in IMTP, linked to early experiments with sensors and actuators in robots.
- **2000–2010:** relatively flat trend, with limited research progress.
- **2015–2020:** steady growth, thanks to advances in smart materials, sensors, and first applications of machine learning.
- **2020–today:** new peak, confirming the topic as mature and relevant, especially for adaptive robotics and industrial/social applications.

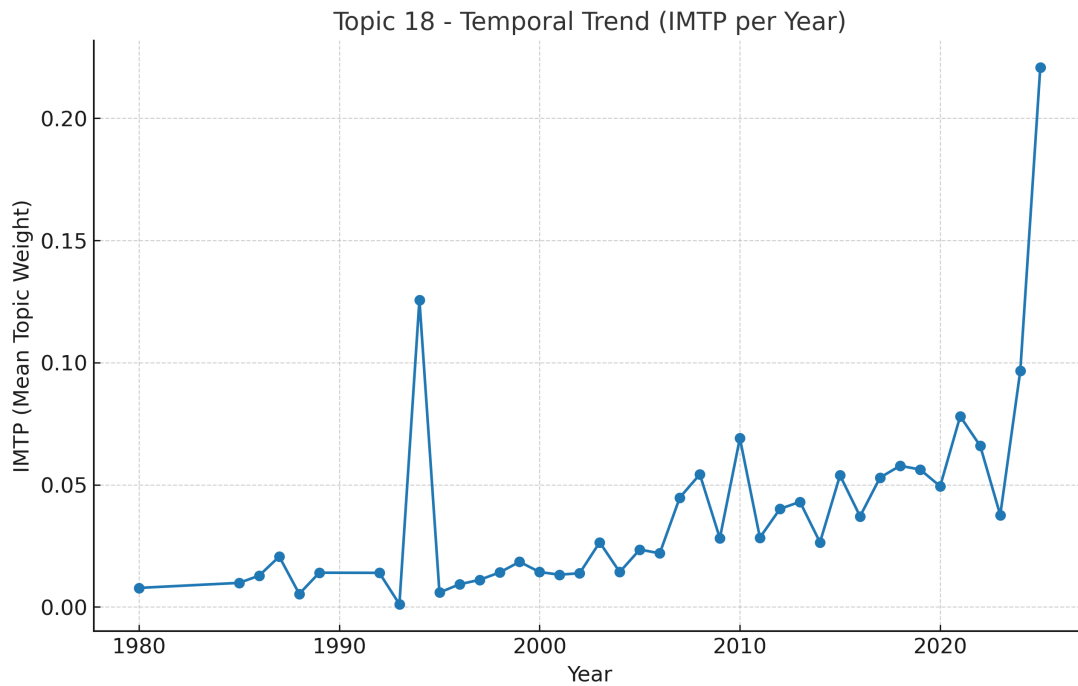


Figure 33: Topic 18: Navigation and Task Allocation in Heterogeneous Humanoid Robot Teams (IMTP per Year)

In short, Topic 18 shows an early but isolated interest in the early '90s, followed by a long quiet phase, and then a clear consolidation in the last decade. The graph makes this progression evident, with the 1990s peak marking exploratory work, and the recent peak reflecting the topic's established importance.

4.19 Topic 19 - Mechanical Design and Additive Manufacturing Optimization in Humanoid Robots

4.19.1 Topic Description

This topic looks at mechanical design and additive manufacturing (AM) optimization for humanoid robots, with a focus on lightweight structures, stiffness-to-weight balance, and how to make parts under process limits. Research explores topology and structural optimization considering SLM issues like anisotropy, thermal distortion, and support strategies. Another focus is integrated design to reduce the number of parts and fasteners, plus post-processing to reach the right tolerances. Case studies on humanoid subsystems such as pelvis modules and wrists show how AM optimization

and material selection (for example Scalmalloy aluminium alloy) can make components lighter, stiffer, and safer for human–robot interaction.

4.19.2 Most Relevant Articles

1. **Junk, Klerch & Hochberg (2019)** — *Structural optimization in lightweight design for additive manufacturing*
Presents optimization for a humanoid pelvis module made with SLM and a novel aluminium alloy. The study integrates weight reduction, stiffness goals, integrated design to cut fasteners, and post-processing for mechanical and thermal accuracy.
2. **Junk, Klerch & Hochberg (2019)** — *Structural optimization in lightweight design for additive manufacturing*
Describes a topology optimization workflow for SLM, considering anisotropy and distortion. Applied to the “Sweaty” humanoid pelvis with Scalmalloy, the work compares design variants and includes an economic evaluation of weight, stiffness, and cost.
3. **Albers, Ottnad & Sander (2009)** — *New concept for wrist design of the humanoid robot ARMAR*
Introduces a new ARMAR wrist design, focusing on lightweight construction, human-like workspace, predictable kinematics, and user safety to support intuitive interaction.
4. **Albers, Ottnad & Sander (2008)** — *Development of a new wrist for the next generation of the humanoid robot ARMAR*
Presents the first prototype of the ARMAR wrist, discussing improvements in dexterity, appearance, and workspace aligned with humanoid interaction needs.
5. **Albers, Sander & Simsek (2010)** — *Development of the actuation of a new wrist for the next generation of the humanoid robot ARMAR*
Details the actuation concept for the ARMAR wrist, explaining actuator and mechanism choices that keep it lightweight while enabling human-like motion and safe cooperation.

4.19.3 Temporal Trends (IMTP per Year)

- **1985–1995:** first signs of interest, with a couple of isolated peaks, mostly early pioneering works.
- **2000–2010:** low curve, with small fluctuations. The topic stayed marginal.
- **2015–2020:** steady rise, with more structured research supported by digital tools and advanced simulations.
- **2021–today:** the trend strengthens, with a new peak that shows consolidation and practical innovations.

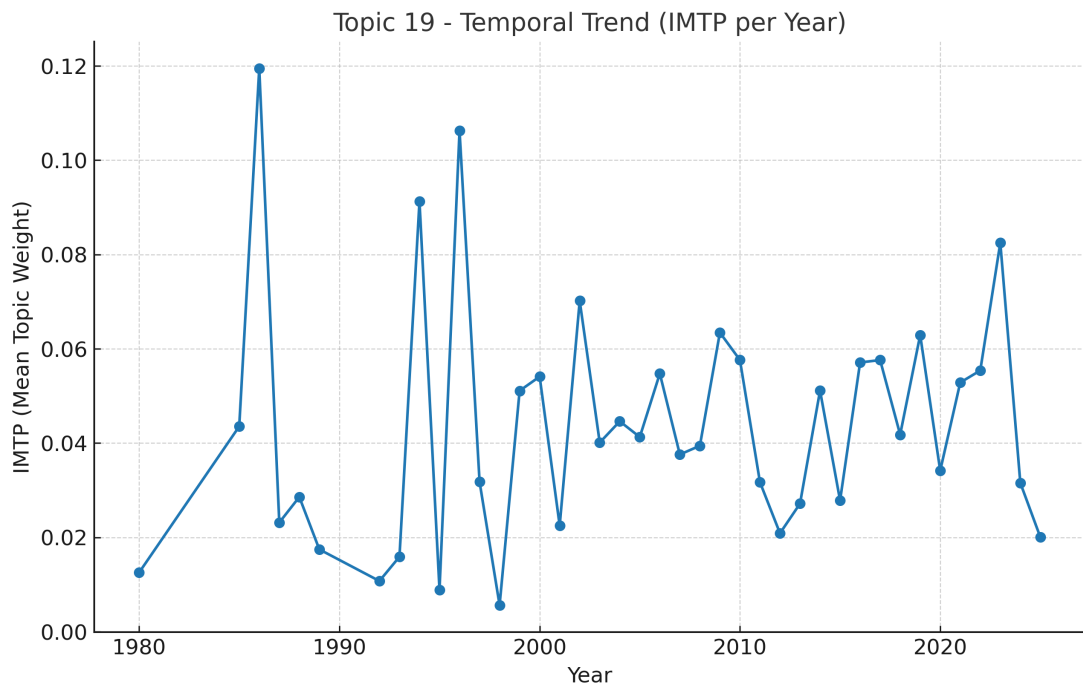


Figure 34: Topic 19: Mechanical Design and Additive Manufacturing Optimization in Humanoid Robots (IMTP per Year)

Topic 19 reflects the trajectory of research fields that begin with scattered experiments, remain quiet for a while, and then resurface when new technologies make it possible to expand and apply earlier ideas. The graph clearly illustrates this pattern, with isolated early peaks and a stronger, more sustained rise in recent years.

4.20 Topic 20 - Flexible Tactile Perception Systems in Human-Robot Interaction

4.20.1 Topic Description

This topic looks at flexible tactile perception systems for humanoid robots and wearable devices. The main goal is to give robots artificial skin and advanced sensing layers that can detect pressure, magnetic fields, or tactile interactions with high precision. Research here connects robotics, materials science, and additive manufacturing. New technologies like flexible electronics, fibre optics, and liquid metal-based sensors help robots and prosthetics get a more natural, human-like sense of touch.

4.20.2 Most Relevant Articles

Based on topic weights, the five most representative publications are:

1. **Shuai et al. (2016)** — *A highly sensitive flexible capacitive pressure sensor with micro-Array dielectric layer*
Introduced a flexible capacitive pressure sensor made with PDMS and silver nanowires. The sensor is transparent, low-cost, and scalable, good for large-area skins in humanoid robots and prosthetics. It shows high sensitivity, fast response, and stability over thousands of cycles.
2. **Mittendorfer & Cheng (2012)** — *Integrating discrete force cells into multi-modal artificial skin*
Presented an artificial skin that combines force cells with sensors for vibration, motion, and temperature. Built with hexagonal unit cells in 3D-printed elastomers, it allows robust, high-frequency force detection and pushes forward the integration of skin in humanoid robots.
3. **Yin et al. (2024)** — *SMF-MMF-SCF-Based Humanoid-Shaped Fiber-Optic Sensor for Wide Range of Magnetic Field Detection*
Developed a fibre-optic magnetic field sensor shaped like a humanoid. It avoids electromagnetic interference and is compact and precise, with

possible uses in healthcare and geology. This shows how tactile systems are expanding beyond pressure to include new sensing types.

4. **Yan et al. (2025)** — *Additively Manufactured Flexible EGaIn Sensor for Dynamic Detection and Sensing on Ultra-Curved Surfaces*
Proposed an additively manufactured electronic skin based on gallium liquid metal (EGaIn). It keeps sensitivity even on curved surfaces and can detect multitouch and sliding. Applications go from tactile sensing in robots to artificial noses, showing how adaptable soft electronic skins can be.
5. **Ntagios & Dahiya (2023)** — *3D Printed Soft and Flexible Insole With Intrinsic Pressure Sensing Capability*
Designed a 3D-printed insole with pressure sensors. Besides use in gait analysis and healthcare, it can help humanoid robots get detailed terrain feedback, improving locomotion and interaction with the environment.

4.20.3 Temporal Trends (IMTP per Year)

The evolution of Topic 20, measured via the Index of Mean Topic Proportion (IMTP), highlights:

- **1980–1995:** almost no contributions, IMTP close to zero. The topic was not yet defined.
- **2000–2010:** first noticeable peaks, linked to early studies on flexible sensors and conductive materials. Growth was irregular but interest started.
- **2015–2020:** consolidation phase, with steady growth. The topic connects with wearable electronics and tactile interfaces in humanoid robots.
- **2021–today:** the peak phase, with high and stable IMTP values. Electronic skin and advanced sensing are now mature technologies, essential in both biomedical and humanoid robotics.

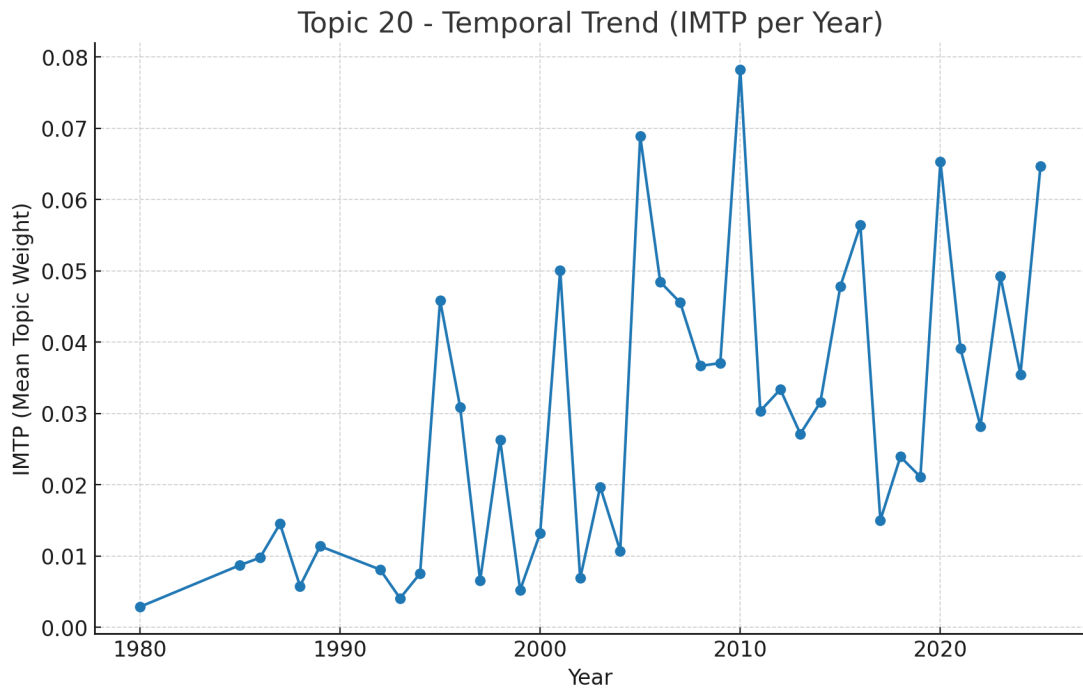


Figure 35: Topic 20: Flexible Tactile Perception Systems in Human-Robot Interaction (IMTP per Year)

In short, Topic 20 has moved from marginal experiments in the early 2000s to a central field in robotics and wearable technologies over the past decade. The graph makes this trajectory clear, with a recent surge confirming its scientific and practical relevance.

4.21 Topic 21 - Actuation and Transmission Systems in Humanoid Robotics

4.21.1 Topic Description

This topic looks at actuation and transmission systems for humanoid robots. The focus is on new mechanical solutions like cycloid vs. harmonic drives, cable differential joints, spherical stepping motors, and shape memory alloy (SMA) actuators. The main goal is to get high efficiency, compact size, low backlash, and lightweight structures to make humanoid motion more natural and precise. Applications go from energy-efficient walking to assistive and rehabilitation robots.

4.21.2 Most Relevant Articles

Based on topic weights, the five most representative publications are:

1. **Sensingier & Lipsey (2012)** — *Cycloid vs. harmonic drives for use in high ratio, single stage robotic transmissions*
Compared cycloid and harmonic drives for robot transmissions. Cycloid drives are thinner and more efficient, with lower reflected inertia, but they have higher backlash and gear ratio ripple. They are useful when compactness and efficiency matter more than precision.
2. **Kratz et al. (2007)** — *Control approach for a novel high power-to-weight robotic actuator scalable in force and length*
Developed a shape memory alloy (SMA) actuator for humanoid robots. Made with bundles of SMA wires, these actuators give high power-to-weight ratio and fast motion. They don't need external sensors because resistance works as a position encoder. This opened a path for lightweight and multifunctional actuation.
3. **Wei et al. (2012)** — *Novel design of biped robot using cable differential joint*
Proposed a cable differential joint used in the BHLEG humanoid platform. This design saves actuator power by redistributing torque, lowering peak loads, and making walking more energy-efficient.
4. **Penić et al. (2017)** — *Assistive humanoid robot MARKO: Development of the neck mechanism*
Presented the neck mechanism of MARKO, a humanoid robot for children with cerebral palsy. Using a low-backlash differential gear system, the neck is accurate, compact, and reliable, while supporting many head movements.
5. **Um et al. (2009)** — *3 Axes rotational and frequency characteristics of a hexahedron-octahedron based spherical stepping motor*
Introduced a spherical stepping motor with a hexahedron-octahedron design. Tested as a joint for humanoid robots, it showed multi-axis torque and frequency responses, giving a new option for compact actuation.

4.21.3 Temporal Trends (IMTP per Year)

The evolution of Topic 21, measured via the Index of Mean Topic Proportion (IMTP), highlights:

- **1988–1994:** first peak years, with new actuators and transmissions. Research explored spherical motors and alternatives to standard gears.
- **1995–2005:** lower activity, but SMA actuators became important for lightweight and assistive robots.
- **2010–2018:** renewed interest, with a peak in 2017. Key studies compared cycloid vs. harmonic drives, designed cable differential joints, and built the MARKO robot neck.
- **2019–today:** stable medium activity, focusing on improving efficiency, compactness, and accuracy instead of proposing disruptive new systems.

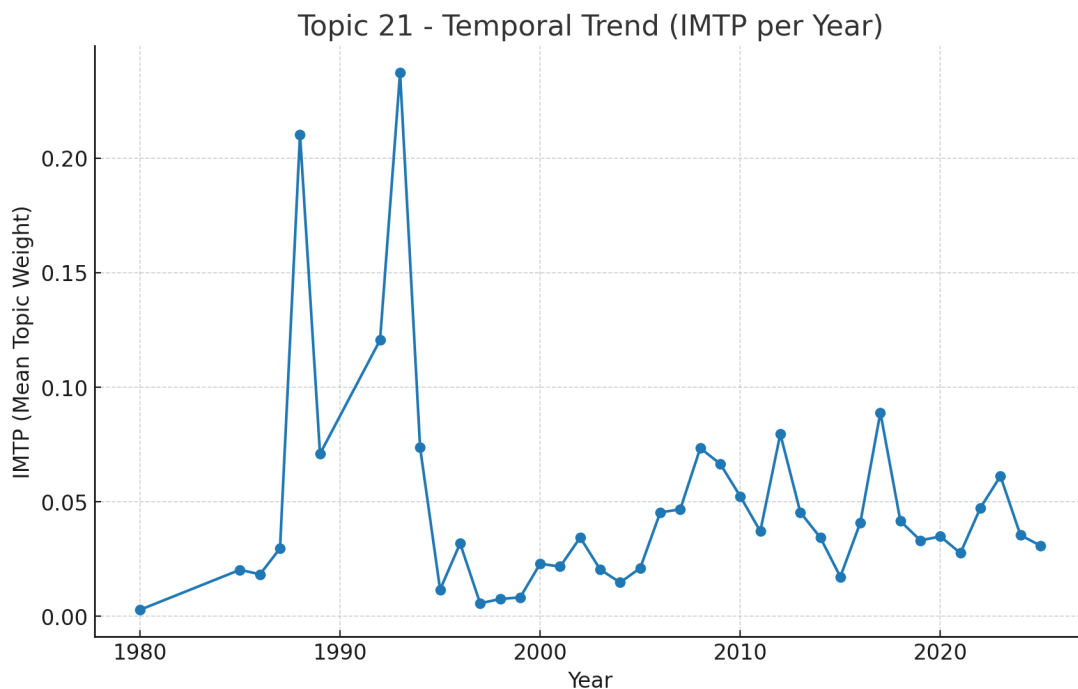


Figure 36: Topic 21: Actuation and Transmission Systems in Humanoid Robotics (IMTP per Year)

Overall, Topic 21 shows an early burst of innovation in actuators and transmissions at the turn of the 1990s, followed by a second, more practical wave of research

in assistive robotics and energy-efficient joints. The figure clearly reflects this: sharp early spikes, then a more targeted but less intense resurgence.

4.22 Topic 22 - Robotic Automation and Smart Manufacturing in Machining and Welding Processes

4.22.1 Topic Description

This topic looks at how anthropomorphic robots are used in advanced manufacturing and welding. The focus is on automation, precision, and productivity. Research explores robotic orbital welding, robotic marking and machining, the integration of multi-axis milling with anthropomorphic robots, and also the role of rapid prototyping in industrial production. These studies aim to make processes faster, reduce manual work, and improve geometric accuracy, showing how robots are becoming more important in both industry and education.

4.22.2 Most Relevant Articles

The five most influential contributions illustrate the breadth of robotic applications in manufacturing:

1. **Silva et al. (2020)** — *Evaluation of toptig technology applied to robotic orbital welding of 304L pipes*
Investigates TopTIG technology for robotic orbital welding of stainless steel pipes. Results show higher welding speed and compact torch design for anthropomorphic robots, but also point out the challenges of robotic GTAW processes.
2. **Lubimyi et al. (2020)** — *A method of determination of average plane of taps of pipes by triangulation method using an anthropomorphic robot*
Proposes a triangulation-based method to find the average plane of pipe taps. This allows anthropomorphic robots to do automated marking operations with better accuracy and less human labour.
3. **Bungau et al. (2014)** — *New tendency of machine tool study based on virtual machining software applied at University of Oradea*

Presents a university project combining virtual machining, CNC, CAM software, and robotic programming in simulated environments. The goal is to support education and research while connecting flexible manufacturing with robotics.

4. **Antunes Simões et al. (2003)** — *Analysis of multi-axis milling in an anthropomorphic robot using the design of experiments methodology*
Analyses multi-axis milling done by an anthropomorphic robot, applying design of experiments (DoE) to optimize surface quality and accuracy in ceramic machining.
5. **Beniak et al. (2014)** — *Accuracy of rapid prototyped models with using of FDM technology*
Focuses on the accuracy of models made with FDM rapid prototyping. The study shows its potential for industrial prototyping, product development, and small-series production.

4.22.3 Temporal Trends (IMTP per Year)

- **2000–2005:** first studies on anthropomorphic robots for multi-axis milling. Mostly experimental and academic, focused on improving surface quality and precision.
- **2010–2015:** consolidation phase with more use of rapid prototyping (FDM) and flexible manufacturing cells, often in university labs. Robots became more integrated in production and training.
- **2018–2022:** strong growth thanks to robotized welding technologies (TopTIG) and automated calibration/marketing methods. This reflects the push for more automation in complex manufacturing.
- **2023–today:** stable trend, with focus on niche applications and optimization instead of big breakthroughs.

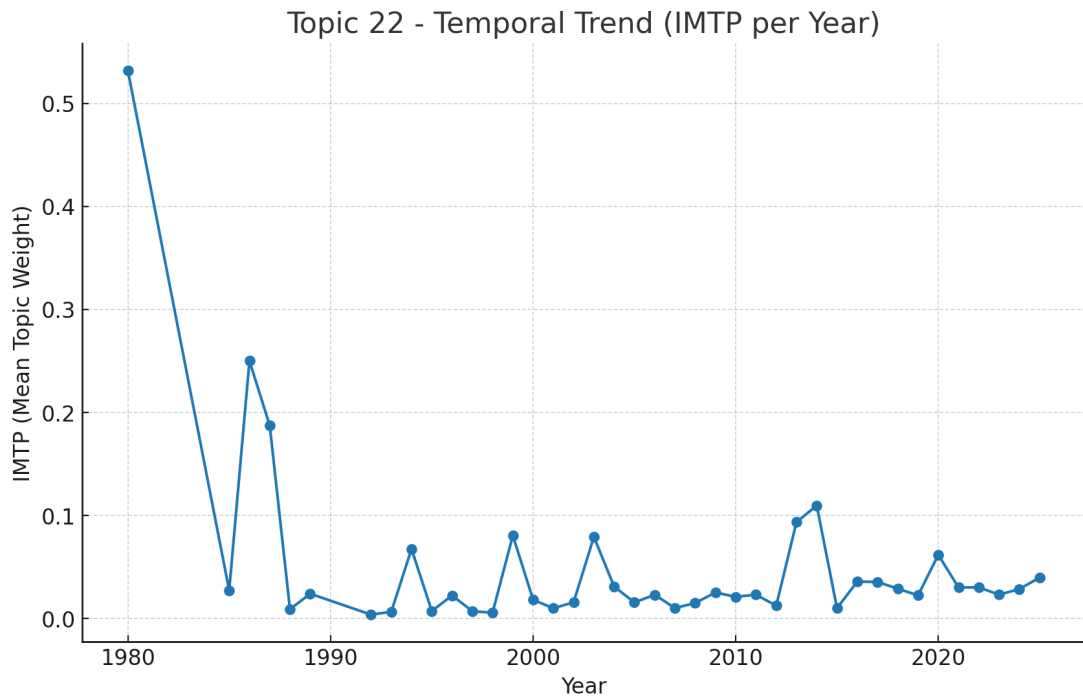


Figure 37: Topic 22: Robotic Automation and Smart Manufacturing in Machining and Welding Processes (IMTP per Year)

In short, Topic 22 reflects the trajectory of an applied industrial field: from academic roots, through adoption in manufacturing workflows, to the maturity of advanced solutions like robotic welding. The figure clearly mirrors this, with recent peaks tied to technological transfer into industry.

4.23 Topic 23 - Remote Teleoperation and Full-Body Control of Humanoid Robots for Industrial Vehicle Operation

4.23.1 Topic Description

This topic looks at remote teleoperation and full-body control of humanoid robots, especially for industrial vehicle operation, mobility assistive devices, and collaborative tasks. The research works focus on teleoperation frameworks that allow humanoids to do complex manipulation and locomotion in real-world environments, often outdoors or in harsh conditions. Important themes include bilateral control, haptic feedback, torso-based human-machine interfaces, and autonomy strategies to keep stability and safety. The general goal is to move humanoid robots out of the lab and use them in practical areas like disaster response, construction, and healthcare.

4.23.2 Most Relevant Articles

Based on topic weights, the five most influential publications are:

1. **Yokoi et al. (2003)** — *A Tele-operated Humanoid Robot Drives a Backhoe in the Open Air*
First outdoor test of a teleoperated humanoid driving an industrial backhoe, even with rain and dust. Introduced technologies for remote control, protection, and stabilization of full-body motion.
2. **Yokoi et al. (2006)** — *A tele-operated humanoid operator*
Expanded the 2003 trial, presenting three key parts of teleoperation: total-body remote control, environmental protection, and autonomous balance control. Showed practical uses for civil engineering and disaster response.
3. **Yokoi et al. (2006)** — *A tele-operated humanoid operator*
Parallel publication confirming the earlier results. Stressed the industrial importance of humanoid teleoperation for construction and restoration work.
4. **Purushottam et al. (2024)** — *Wheeled Humanoid Bilateral Teleoperation with Position-Force Control Modes for Dynamic Loco-Manipulation*
Introduced Dynamic Loco-Manipulation (DLM) with bilateral teleoperation. Showed humanoids doing heavy tasks like slotting boxes and carrying loads with a human partner, using haptic feedback and position–force control.
5. **Chen et al. (2024)** — *Torso-Based Control Interface for Standing Mobility-Assistive Devices*
Proposed a torso-based, hands-free interface for assistive devices. Demonstrated how coupling human torso movement with the robot allows more natural locomotion while keeping the hands free for other tasks.

4.23.3 Temporal Trends (IMTP per Year)

The temporal analysis of Topic 23 highlights three distinct waves:

- **2000–2005:** first experiments with humanoid teleoperation in industrial vehicles, like driving a backhoe. Mostly proof-of-concept showing feasibility in outdoor conditions.
- **2006–2010:** more publications, consolidating the teleoperated humanoid operator idea for civil engineering and dangerous environments.
- **2015–2020:** stable interest, with research on robustness, protective systems, and full-body control to make humanoids usable in real tasks.
- **2021–today:** renewed growth with bilateral teleoperation and position/force control, opening applications in logistics, construction, and healthcare.

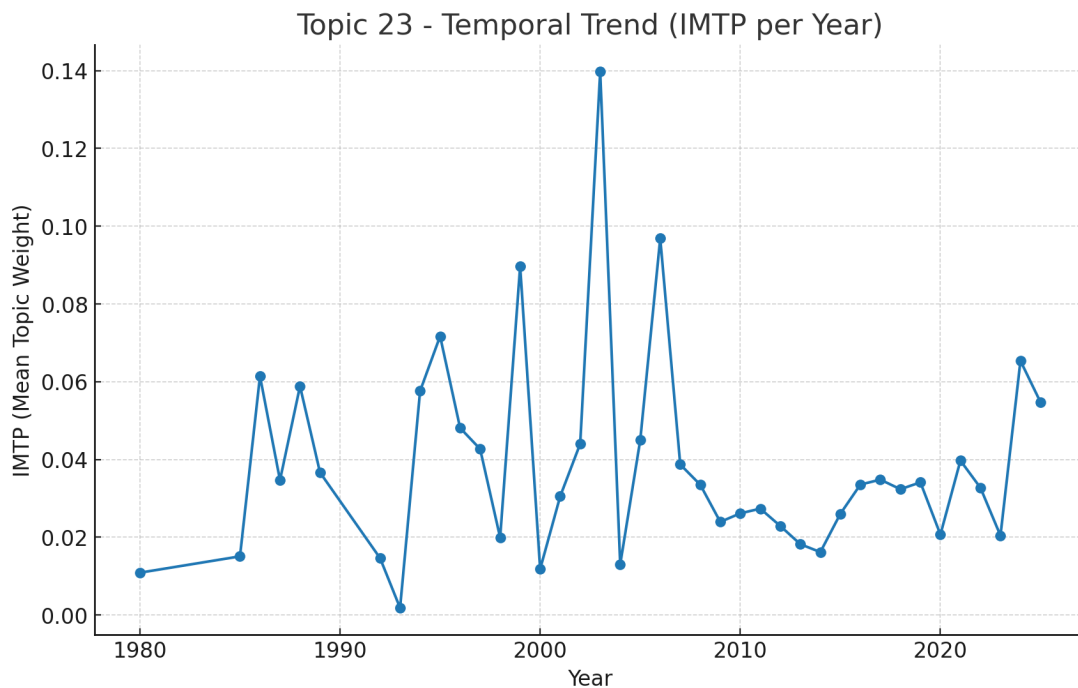


Figure 38: Topic 23: Remote Teleoperation and Full-Body Control of Humanoid Robots for Industrial Vehicle Operation (IMTP per Year)

Overall, Topic 23 illustrates a shift from early visionary demonstrations to practical teleoperation systems, with the chart showing an early peak in the 2000s and a strong revival after 2020, driven by advances in control and human–machine interfaces.

4.24 Topic 24 - Anthropomorphism in Robots: Different Preferences Depending on the Application Domain

4.24.1 Topic Description

This topic looks at how anthropomorphism and context influence trust, acceptance, and interaction between humans and robots. Research shows that the design of the robot (anthropomorphic or technical), the application domain (industrial, service, social), and how people perceive failures affect trust and user preference. A main point is that anthropomorphism is not always good: in social contexts people prefer human-like robots, while in industry they usually prefer more functional and technical designs. The studies also underline that trust is complex, not only based on performance, but also on transparency, empathy, and perceived purpose.

4.24.2 Most Relevant Articles

Based on topic weights, the five most relevant contributions are:

1. **Roesler et al. (2022)** — *Why Context Matters: The Influence of Application Domain on Preferred Degree of Anthropomorphism and Gender Attribution in Human–Robot Interaction*
Showed that preferences for anthropomorphism depend on context: lower in industrial domains, higher in social ones, with functional names preferred over gendered names.
2. **Salem & Sumi (2024)** — *A Comparative Human-Robot Interaction Study between Face-Display and an Advanced Social Robot*
Compared a low-cost retro-projected robot with the Furhat system. Furhat performed better in anthropomorphism, trust, and empathy,

while anime-style faces were rated higher in pleasantness and warmth for both robots.

3. **Roesler (2023)** — *Anthropomorphic framing and failure comprehensibility influence different facets of trust towards industrial robots*

Studied how anthropomorphic framing and understanding of failures affect trust in industrial robots. Found that framing increased perceived transparency but not actual transparency, showing a double-edged effect.

4. **Roesler et al. (2020)** — *The effect of anthropomorphism and failure comprehensibility on human-robot trust*

Showed that anthropomorphism in collaborative industrial robots does not always increase trust. Sometimes reliability was perceived as lower, proving that design must fit the context and user expectations.

5. **Biermann et al. (2021)** — *How context and design shape human-robot trust and attributions*

Explored how context (production vs. care) and robot design shape trust. Found that technical-looking robots were more trusted in production, while anthropomorphic robots were seen more positively in care contexts.

4.24.3 Temporal Trends (IMTP per Year)

The evolution of Topic 24 highlights the growing importance of context-sensitive trust in HRI:

- **2000–2010:** the topic was almost absent, with IMTP values near zero. Research was mostly focused on technical aspects of robotics, leaving social and perceptual dimensions aside.
- **2015–2019:** a growth phase begins, with the first systematic studies on how anthropomorphism affects trust and how robot design needs to adapt depending on the domain (industrial, social, healthcare).

- **2020–today:** the topic takes off, reaching its highest IMTP values and showing a significant increase in publications. Recent work highlights that anthropomorphism and design choices do not have a universal effect but are strongly context-dependent. For instance, technical and functional designs are preferred in industrial settings, while human-like features are more valued in social and healthcare domains.

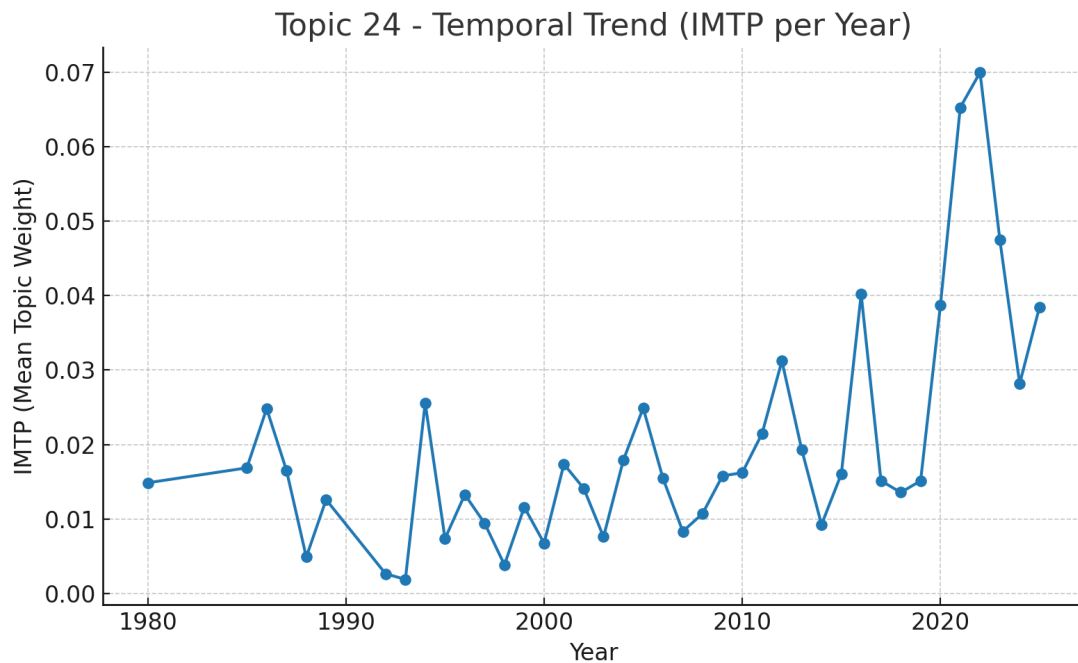


Figure 39: Topic 24: Anthropomorphism in Robots: Different Preferences Depending on the Application Domain (IMTP per Year)

Topic 24 shows a clear shift: from a marginal concern to a central issue in human–robot interaction. The trend underlines that it is no longer enough to build technically capable robots, today, success also depends on designing them to be trusted, understood, and accepted by people. The chart clearly illustrates this, with sharp growth in the last five years.

5. Case Study: Amazon and the Humanoid Robot Digit

5.1 Introduction

Amazon has been for years at the front in robotizing its distribution centers. In their warehouses, called fulfillment centers, there are hundreds of thousands of industrial robots, mainly autonomous mobile robots (AMRs) originally developed by Kiva Systems, acquired by Amazon in 2012. They are used to move shelves automatically, and they work together with vision systems and artificial intelligence to optimize the internal flows (Amazon, 2025).

On top of this strong technology base, in 2023 Amazon started a pilot project with humanoid robots. The goal is to explore new possibilities of automation in tasks that need advanced manipulation and interaction in complex environments (The Guardian, 2025).

5.2 Amazon x Digit Case

The robot used in the pilot is Digit, developed by the American startup Agility Robotics, created in 2015 as a spin-off of Oregon State University. Digit is about 175 cm tall, weighs 65 kg, can carry loads up to 16 kg, and is designed to work in standard warehouses. It has long and flexible legs that let it go upstairs and move in spaces that are not optimized for automation. Its modular arms allow it to grab and handle boxes and containers, so it is good for tasks like tote picking and moving (Agility Robotics, 2024). Digit is connected with the cloud platform Agility Arc, that makes possible the coordination of robot fleets and the integration with warehouse management systems. This is very important for scalability. Agility already said the goal is to produce 10,000 units per year in the RoboFab of Salem, Oregon, opened in 2023. This is the first factory in the world made only for humanoid robots (Agility Robotics, 2023).



Figure 40: Digit robot x Amazon – tote picking task (SRISHI, s.d.)

5.3 Goals and expectations of the Pilot

The pilot with Digit started in some Amazon warehouses in the USA in 2023. The main idea is not to replace workers, but to integrate them with robots for better collaboration:

- Reduce repetitive and heavy tasks, like lifting and moving packages.
- Increase worker safety, lowering ergonomic risks and accidents from manual handling.
- Have more flexibility, because Digit can move in places made for humans, not only in areas made for traditional mobile robots.

Amazon expects better productivity and the chance to start a more “adaptive” automation, able to work in changing and not always predictable situations, different from the very standardized production lines (TechCrunch, 2024).



Figure 41: Digit working for Amazon (roastbrief, s.d.)

5.4 Limits, Risks and Perspectives

Even if Digit has potential, using humanoids brings some important challenges:

- **Reliability:** the technology is still new, and robots must show they can work for long shifts in complex environments without problems.
- **High costs:** developing and producing humanoids is still much more expensive than using normal industrial robots, around \$300,000 (Rauf, 2025).
- **Social and organizational acceptance:** workers need to see the robot as a support, not as a danger, and companies must adapt processes to use its full potential.

Anyway, Amazon and Agility Robotics have very ambitious goals. Beside the mass production of Digit, they want to integrate humanoids at large scale before 2030. This could create a new paradigm where humanoids work together with industrial robots in global logistics chains (MIT Technology Review, 2025).

5.5 Conclusion

The Amazon × Digit case is an important step in the integration of humanoid robots in manufacturing and logistics. After automating many activities in its warehouses with traditional robots, from robotic arms to autonomous mobile platforms, Amazon decided to test a new generation of technology. This technology has the potential to make the human-machine hybrid workforce much stronger (The Guardian, 2025).

Digit is not only a logistic support, but also a platform that shows many of the topics from our analysis. On one side, it is connected to *Topic 9* (mechanical systems analysis and simulation), because of the complex mechanisms like biped locomotion and load management. On the other side, it is linked to *Topic 10* (human-robot interaction and intelligent agents), since the robot was designed to work closely with human operators, moving in the same spaces and adapting to the unstructured warehouse environment. Finally, it also matches with *Topic 5* (collaborative robots for assembly and inspection), which shows how robotics is moving to integrated solutions, where robots become partners and not just tools.

This case study supports the main idea of the thesis: humanoid robots are not only lab prototypes anymore but are starting to enter the industrial value chains. The choice of Amazon is not only a tech experiment, but a clear sign that global companies now see this technology as part of their future strategies. Looking forward, the humanoid robots could expand the applications of industrial robotics, with big impacts on productivity, worker safety, and the organizational transformation of factories.

6. Conclusions

6.1 General Overview

This thesis wanted to study the role of humanoid robots in manufacturing and related fields. To do this, two different approaches were used: first a literature review, to understand how humanoid platforms evolved from the beginning until today, and second a topic modelling analysis on 1,330 papers taken from Scopus.

The review helped to see the technical progress of humanoid robots, from first prototypes like WABOT and ASIMO to more recent machines such as Atlas, Digit or Optimus. The analysis of the platforms also showed how these robots slowly moved from being only research demonstrators to having more practical uses, for example in industrial environments.

The topic modelling gave a more quantitative view. With Structural Topic Modelling (STM), 24 main topics were found, covering areas like platform design, locomotion, dexterous manipulation, human–robot interaction, sensing systems, and also industrial and collaborative applications. Some topics had more weight than others, showing the areas where the research community worked the most.

In this way, the two approaches completed each other: the literature review gave the story and context, while the topic modelling gave structure and numbers. Together they make a more complete picture of humanoid robotics.

6.2 Main Findings

From the analysis, some important elements can be underlined.

The historical evolution of humanoid robotics can be divided into three main phases:

- I. **Explorative phase (1970–1995):**
In this period, research was mostly about the mechanical feasibility and the first experimental platforms. Representative topics are Topic 11 - Kinematics

and Stiffness Optimization of Anthropomorphic Robot Arms, focused on the design of robot arms and stiffness optimization, and Topic 22 - Robotic Automation and Smart Manufacturing in Machining and Welding Processes, that shows the first, still limited, attempts to use anthropomorphic robots in industrial scenarios.

II. **Expansion** **phase** **(1995–2010):**

This is the phase of the big humanoid projects. The most representative is Topic 3 – Design and Evolution of Humanoid Robotic Platforms, which is also the topic with the highest overall weight (7%, see [Table 3: Topic labels, keywords and sources](#)). It shows clear peaks during the development of iconic robots like ASIMO and HRP, confirming its central role in this phase. In the same period, also Topic 21 - Actuation and Transmission Systems in Humanoid Robotics, with studies on new actuators (cycloidal, SMA, cable differential), and Topic 6 - Locomotion and Dynamic Balance Control in Humanoids, focused on biped walking and balance control, became increasingly relevant.

III. **Application** **phase** **(2015–today):**

In the most recent years, the attention moved to practical applications, especially in industrial and collaborative contexts. Some representative topics are Topic 18 – Navigation and Task Allocation in Heterogeneous Humanoid Robot Teams, that shows humanoids in complex and multi-robot environments, Topic 20 - Flexible Tactile Perception Systems in Human-Robot Interaction, about electronic skins and advanced tactile sensors, and Topic 24 - Anthropomorphism in Robots: Different Preferences Depending on the Application Domain, focused on trust, acceptance, and context. On the more technical and industrial side, also Topic 14 - Additive Manufacturing and Lightweight Structural Design in Humanoids and Topic 15 - Safety, Compliance and Physical Human-Robot Collaboration are relevant, dealing with lighter structures and safe physical interaction with humans.

To make this evolution more clear, a graph was included with three topics selected as examples of each phase: Topic 11 for the explorative phase, Topic 3 for the expansion phase, and Topic 18 for the application phase. The [Figure 42](#) shows the shift from

early technical and mechanical studies to the design of complete platforms, and finally to applications in real and complex scenarios.

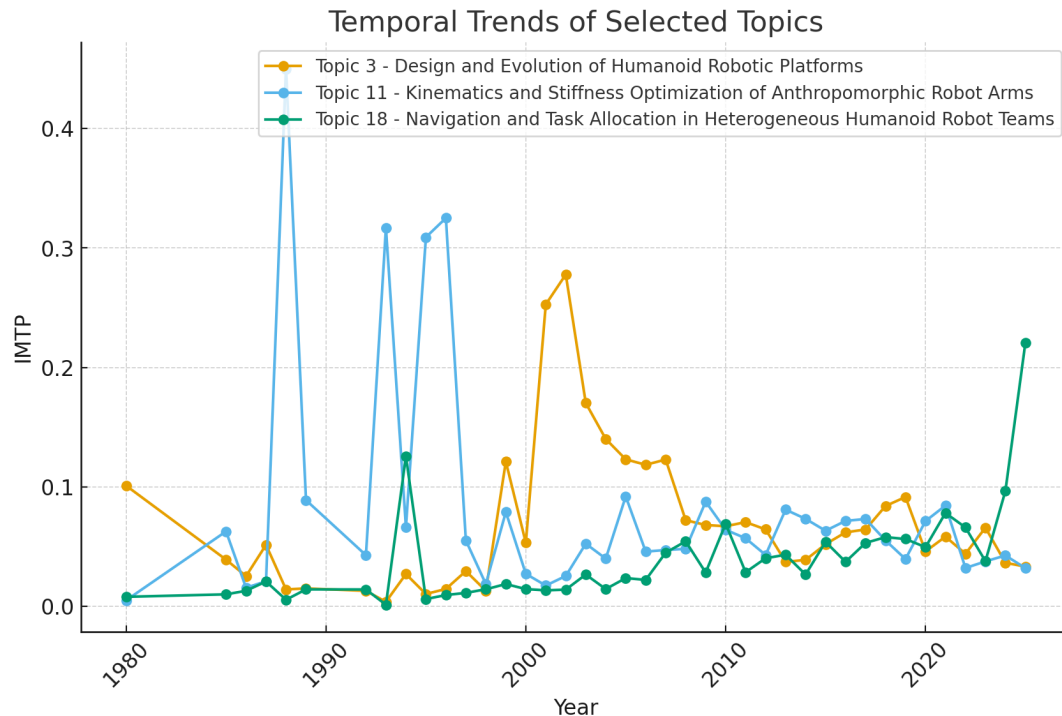


Figure 42: Temporal Evolution of Selected Topics (Topic 11, Topic 3, Topic 18) Representing the Three Phases of Humanoid Robotics

This interpretation confirms that humanoid robotics is no longer limited to laboratory prototypes: research has progressively moved toward concrete problems of production, interaction, and collaboration, opening the way for integration in industrial and logistic contexts.

6.3 Limitation of the Thesis

Some limits must be mentioned:

- **Database:** the corpus was only from Scopus. This means not all of the other sources like IEEE Xplore, patents, or industrial reports were included. This means the picture is big, but not complete.

- **Proceedings:** many conference proceedings were inside the corpus. In Scopus, sometimes a whole conference is registered as one document, and this made some topics look heavier than they really are. This is a weakness of the dataset.
- **Limits of topic modelling:** STM is useful to find patterns, but it does not really “understand” the deep meaning of texts. Some topics were overlapping or not very clear, and this required manual work to label and interpret them.
- **Case study:** the Amazon × Digit pilot is very new, and information is still limited. We don’t know yet the full results or how much it will really change the work in warehouses.

6.4 Future perspectives

Looking at the future, humanoid robotics seems ready for a new phase:

- **Better technology:** robots will probably become more reliable, less expensive, and more energy efficient, making them easier to use in industry.
- **Smarter AI:** new AI models, including generative AI, will improve perception, decision making and communication, making collaboration with humans more natural.
- **More applications:** not only in manufacturing, but also in logistics, healthcare, construction, and maybe even domestic use.
- **Organization of work:** companies will have to change processes and train workers to collaborate with humanoids in an effective way.

6.5 Final remarks

This work wanted to give a structured picture of humanoid robotics in manufacturing. By joining the literature review and the topic modelling, it shows both the story and the main research directions.

The analysis suggests that humanoid robots are moving from the lab to real applications, even if many technical and organizational challenges are still there. The case of Amazon × Digit is an example: it is still a pilot, but it shows that big companies are seriously testing humanoids for logistics and production.

In conclusion, humanoid robots are not only a technological curiosity: they are becoming part of industrial strategies and could, in the future, transform the way humans and machines work together.

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