Human-Robot Interaction
from Dance Partner Robot to Co-worker Robot

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http://www.irs.mech.tohoku.ac.jp

Outline

- Challenges and Opportunities of Robotics
  - Overview of Robotics (by JST in 2009)
- Examples of Physical Human-Robot Interaction
- Dance Partner Robots
  - MS DanceR and PBDR
  - RoboDANTE
- PaDY
  - PaDY in a factory
- Conclusions

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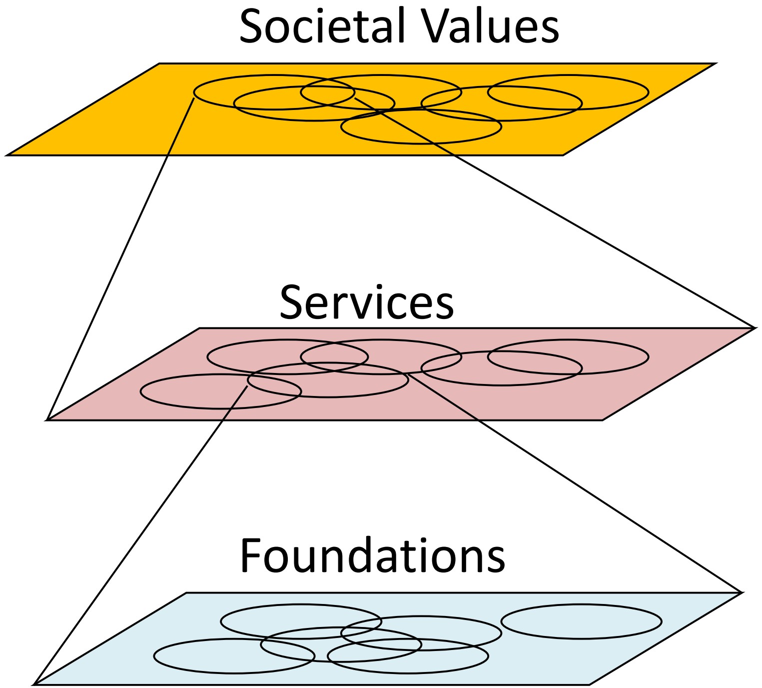
Robotics

- Societal Level
- Service Level
  - Service enablers
- Fundamental Technologies Level



Societal Values

- For Individuals
- For Communities
  - For Families
  - For Industries
  - For Local Government
  - For Nations
- For the Globe

★Quality of Life

★Industrial Competitiveness

★Global Issues

Challenges and Opportunities of Robotics

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Social Value	Global Level	Community Level		Quality of Life	
Services	·Environmental Monitoring ·Natural Resources Exploration and Development ·Space Exploration ·Deep Undersea and Underground Exploration ·Anti-terrorism ·Rescue Operation ·Prevention of Infectious Diseases	·Government Service ·Agriculture ·Forestry ·Fishery ·Mining ·Manufacturing ·Construction ·Wastes Treatment/ Management	·Utilities ·Retailer/Wholesaler ·Transportation ·Communication ·Service Industries ·Medicine ·Education ·Research and Development	·Medicine ·Therapy ·Daily Life Assist ·Healthcare ·Rehabilitation ·Mental care ·Learning ·Child care ·Housekeeping	·Security ·Mobility ·Shopping ·Hobby ·Entertainment ·Sports ·Comfort Life ·Watch ·Communication

Service/Application-oriented Robotics

Emerging Technology

- Cyborg (Cybernetic organism)
- Stochasticity in Robotics
- Performance evaluation and Benchmarking
- Ambient intelligence
- Autonomous Robots
- Teleoperation
- Robotic Emotion (artificial emotion)
- Software framework
- Social Concerns
- Functional Safety
- Nano-micro Robotics
- Human Modeling
- Wearable Technology
- Service Contents Design

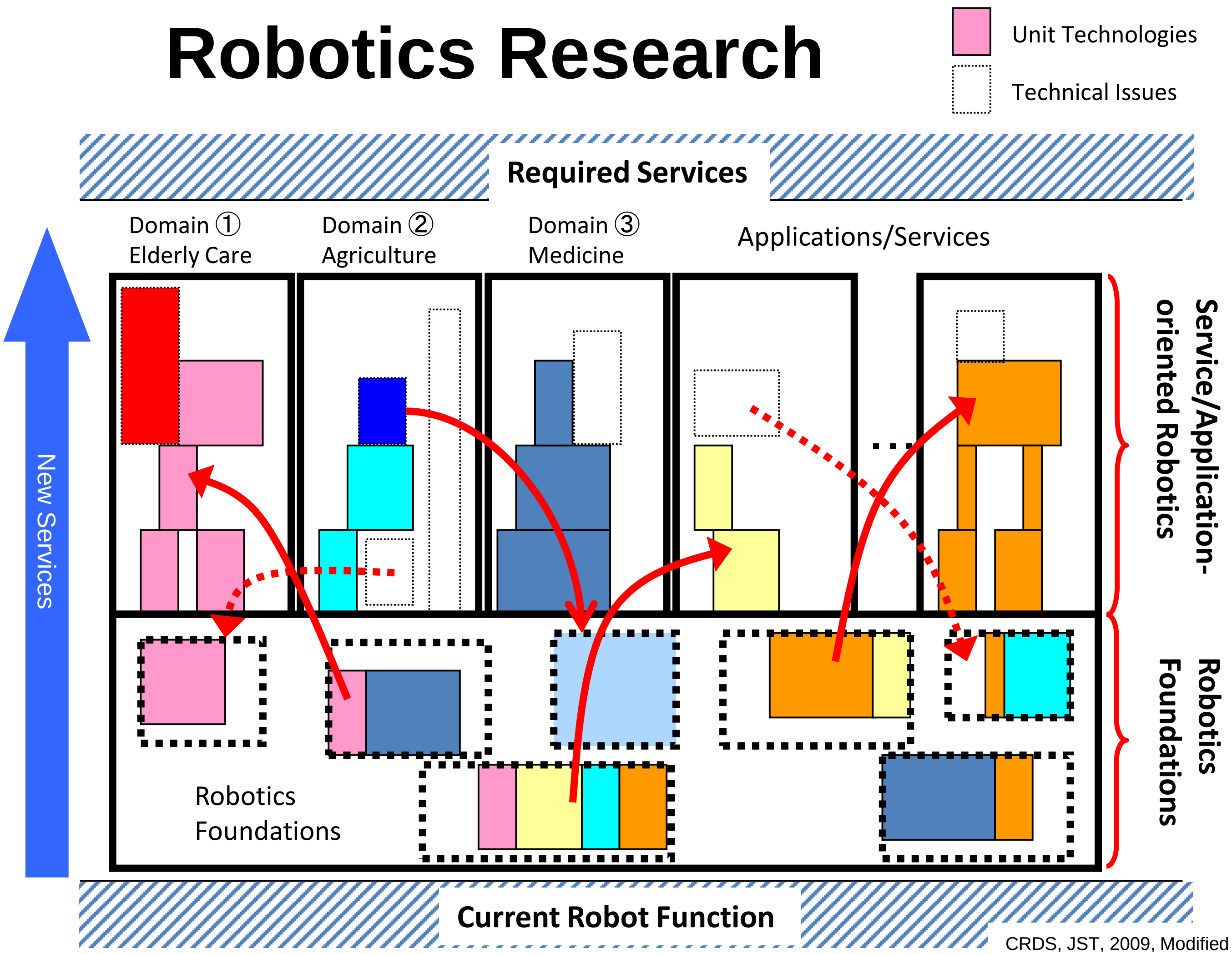
Fundamental

- Robot Systems Integration
- Human Robot Interaction
- Real-world Real-time Intelligence
- Spatio-temporal System Design
- Sensing and Machine Cognition
- Robot Kinematics and Dynamics
- Manipulation
- Mobility
- Actuation
- Physics-based Control

Robotics Foundations

CRDS, JST, 2009, Modified by Kosuge, August, 2011

Robotics Research



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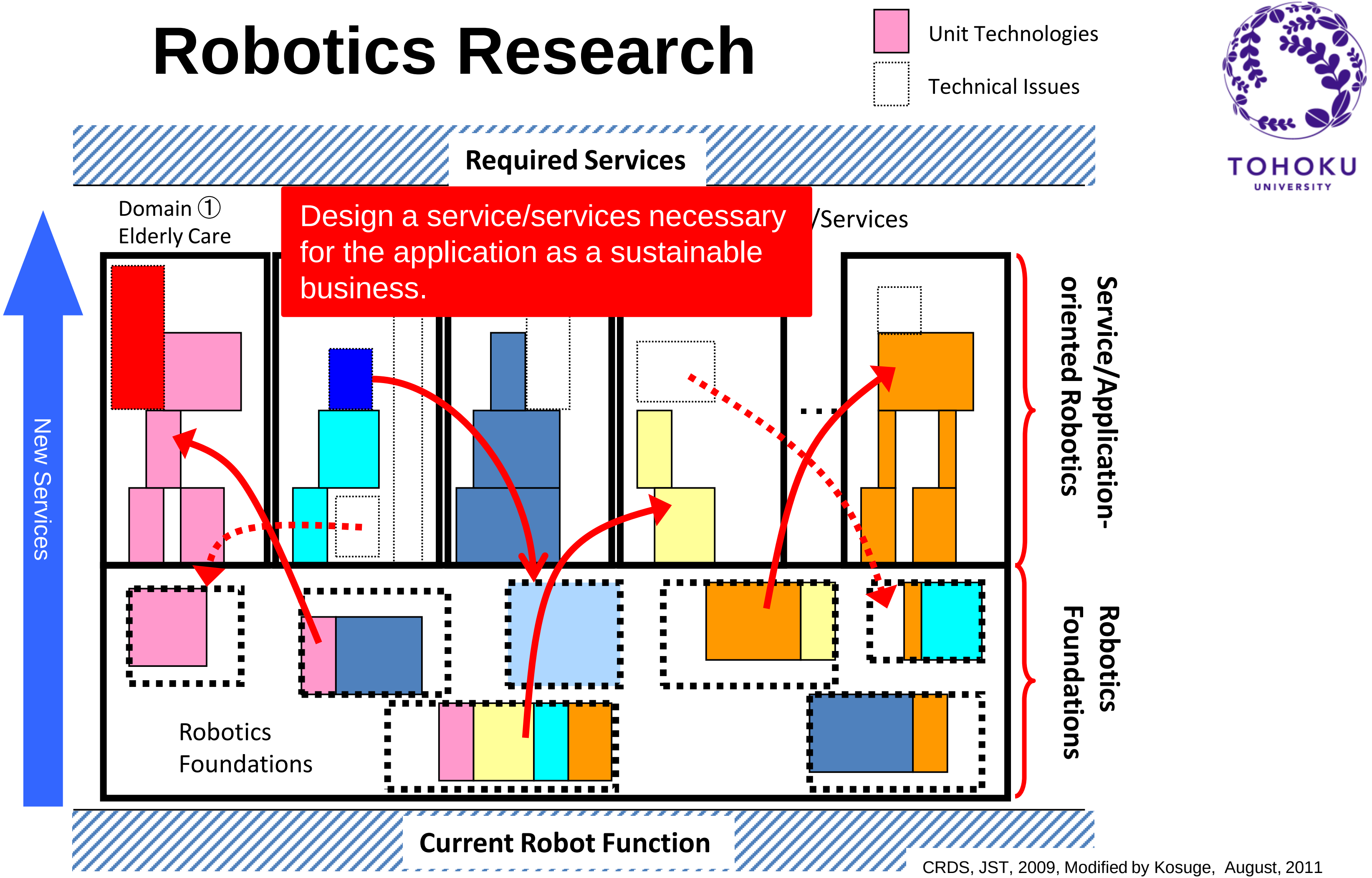
Robotics Research



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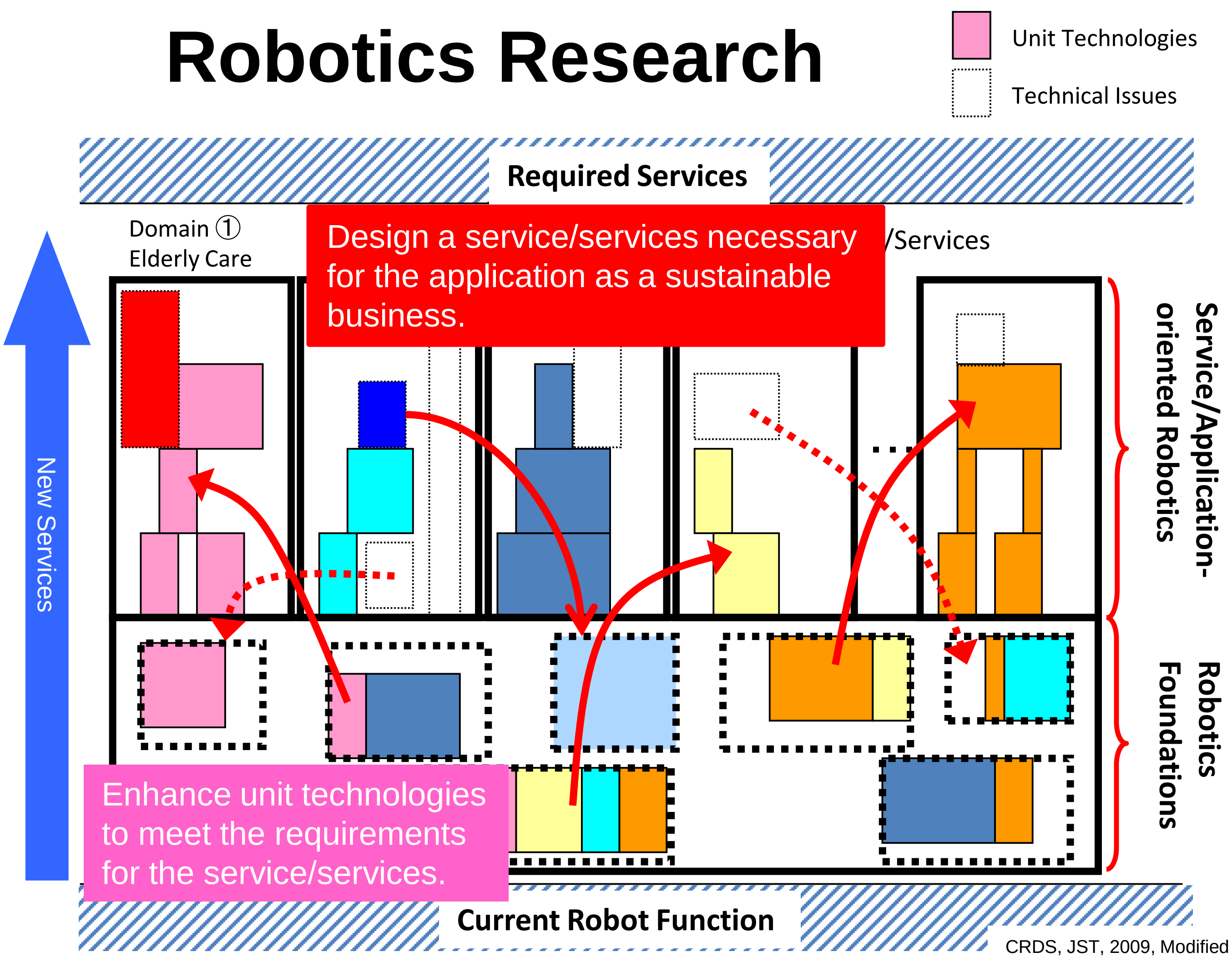

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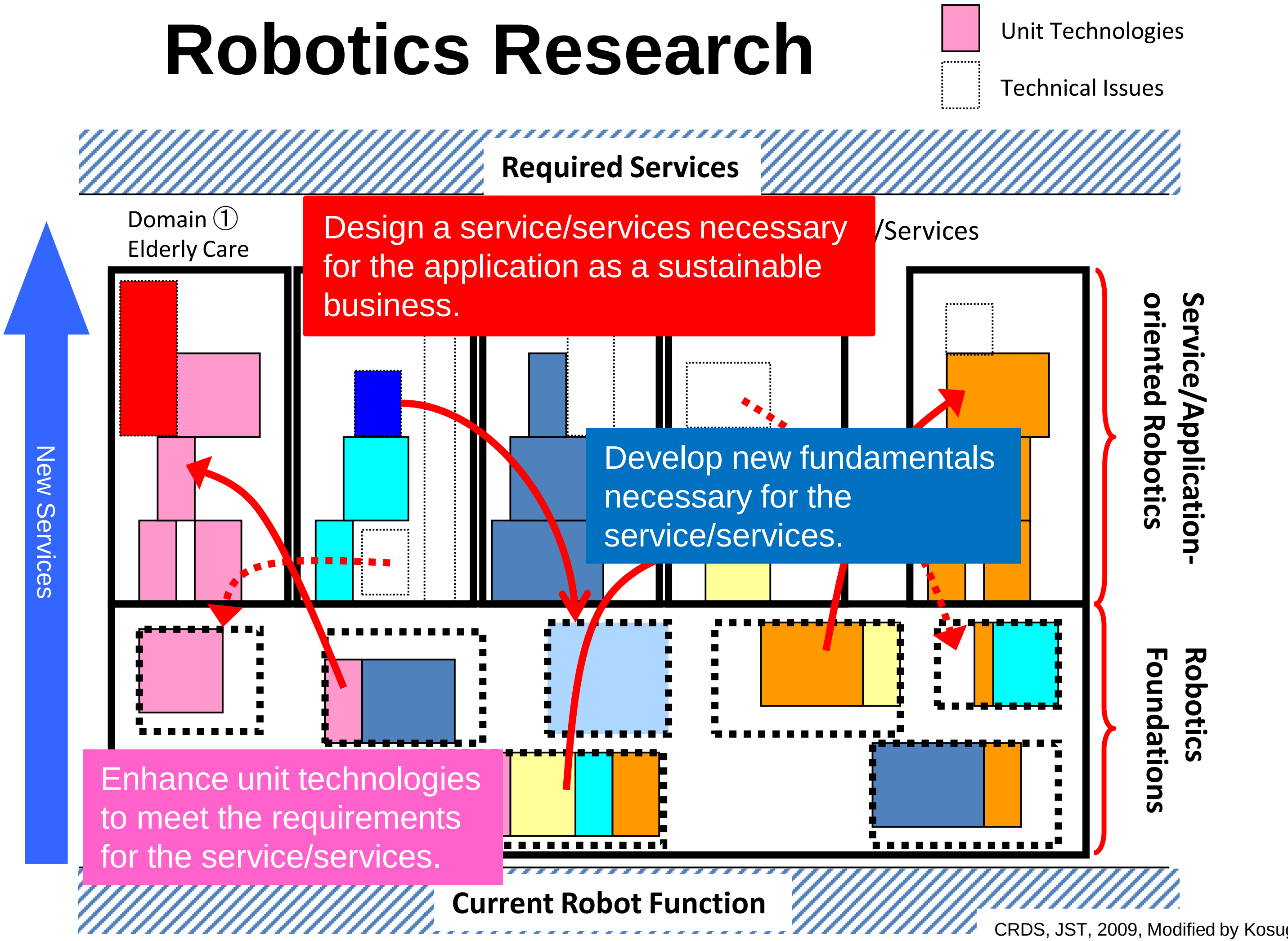

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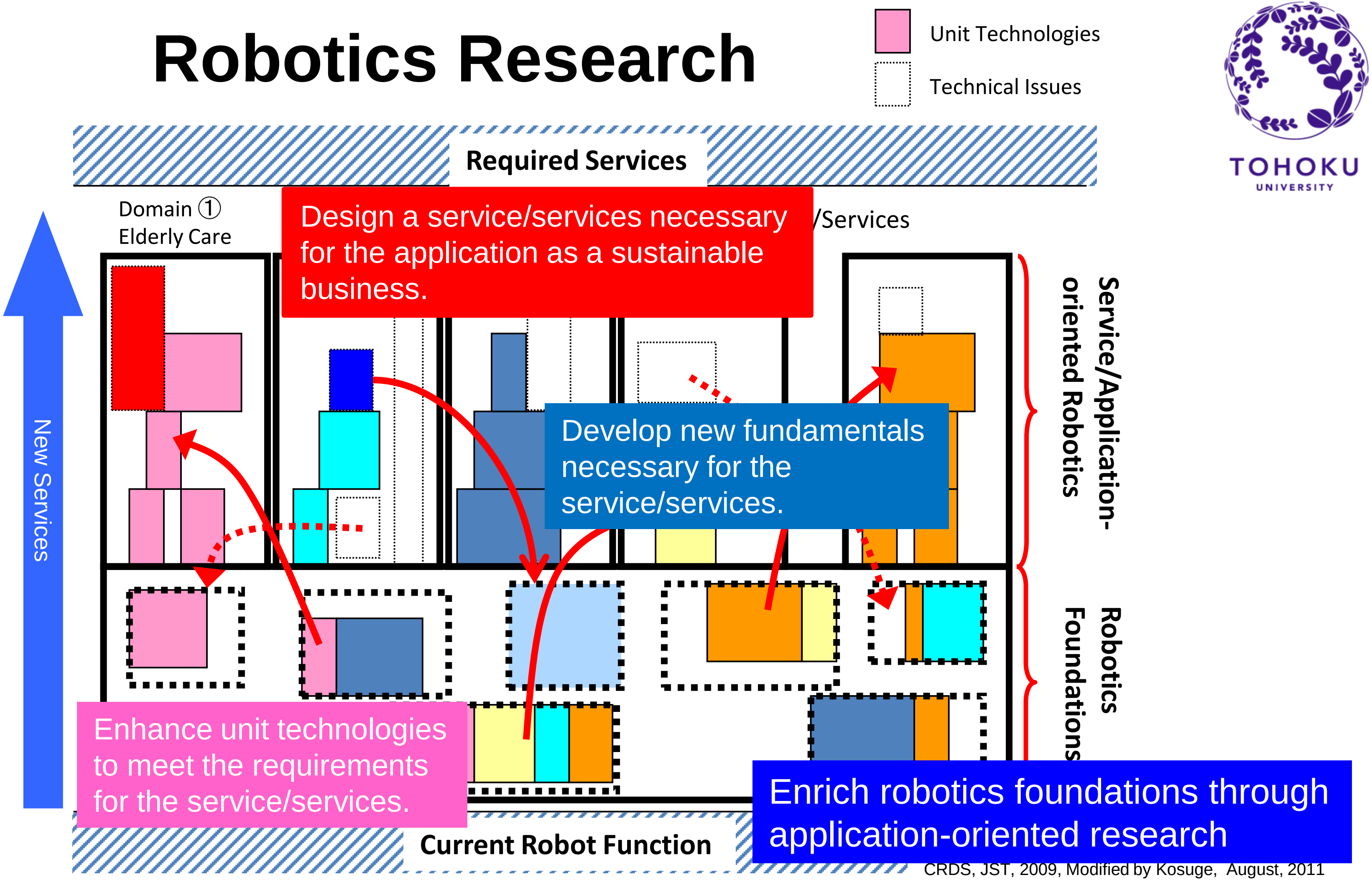

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Systems Robotics

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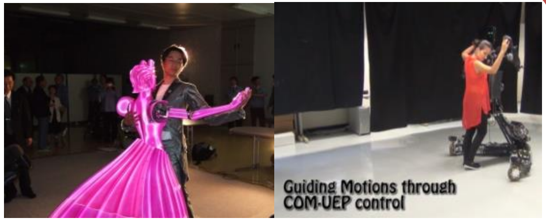
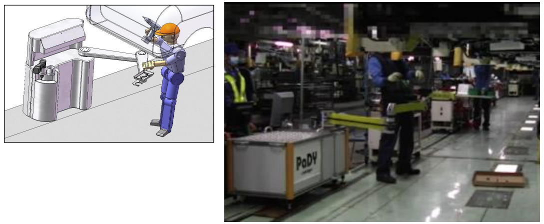
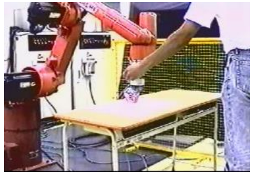


Intention Recognition/Transfer



Robot Co-worker "PaDY"
(in-time Parts/tools Delivery robot)



Stable Power Augmentation

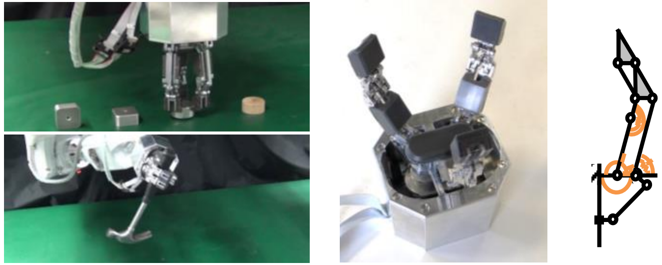
Human Robot Coordination

Human-Robot Interaction

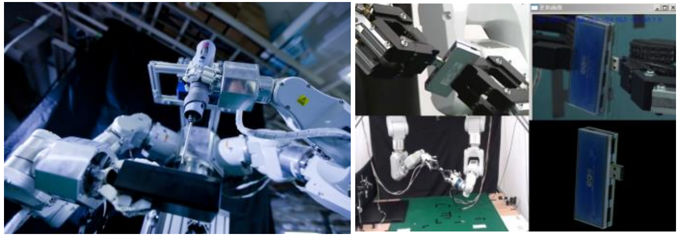
Walking Helper

Power Assisted Chair Cycle

Assistive Robotics



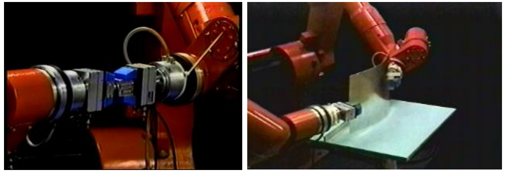
Universal Robot Hand uGRIPP with Two-degrees of Freedom



Integration of Visual and Impedance Servo

Universal Manipulation

Intelligent Car Transportation Robot
iCART and iCART II



Assembly and Manipulauion by Dual
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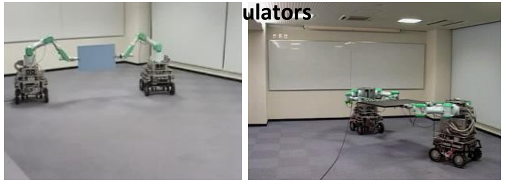

Mobile Manipulators

Multiple Robots Coordination

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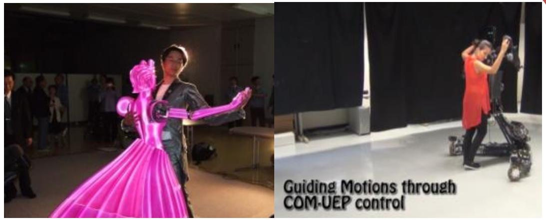
Human-Robot Interaction



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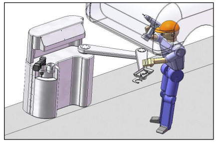

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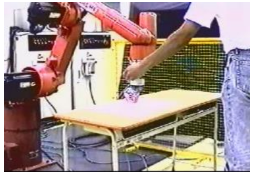

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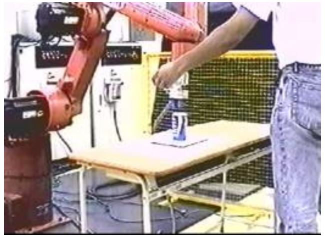
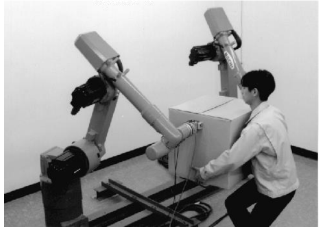
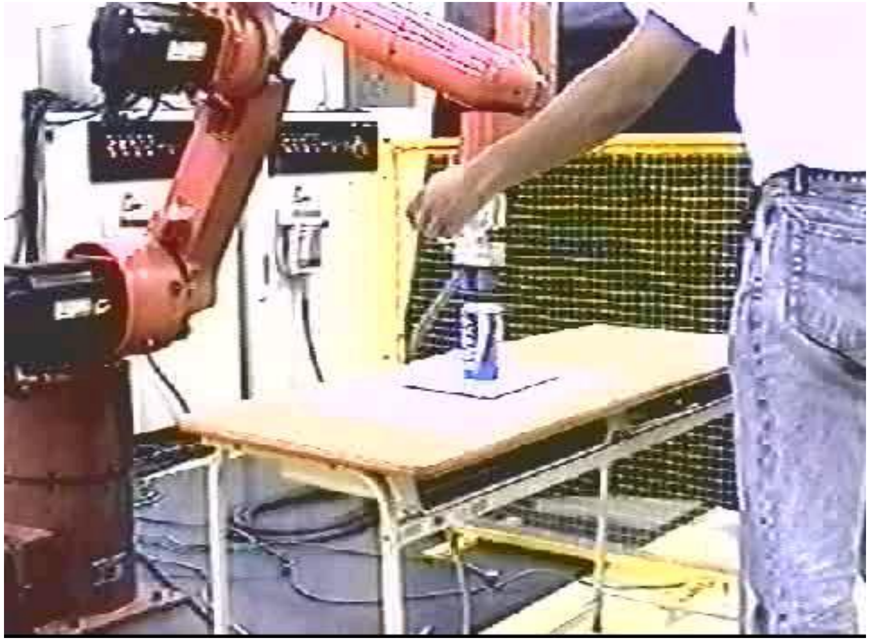
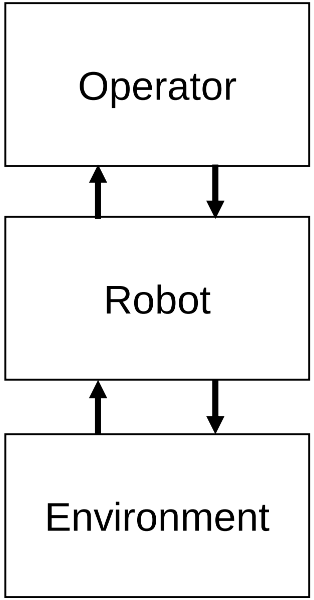



Human Power Augmentation

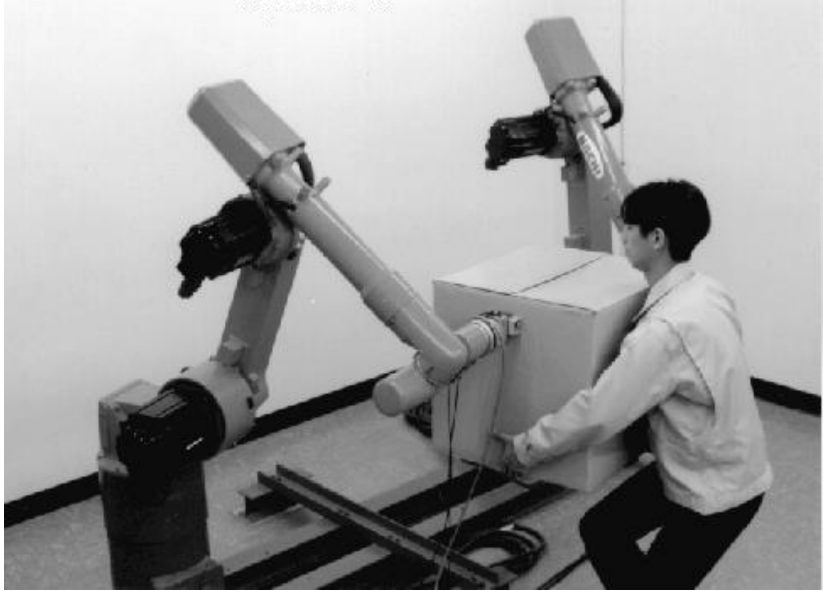


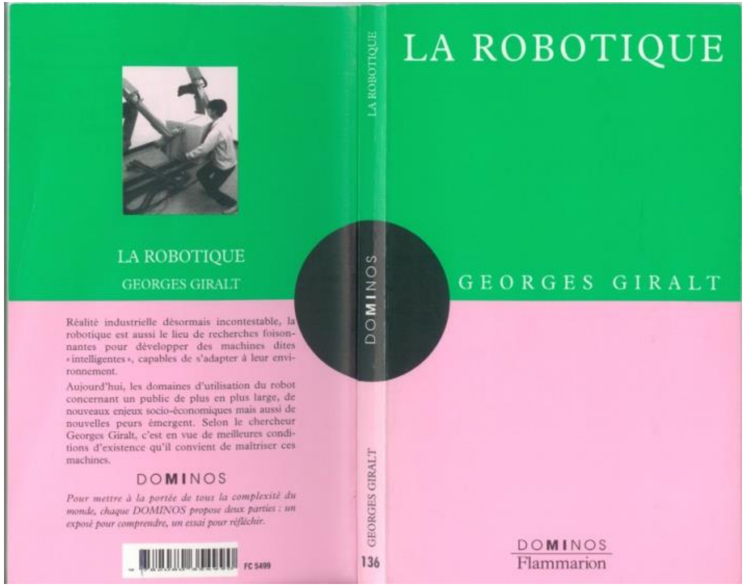


Human Power Augmentation

[1] K. Kosuge, Y. Fujisawa, T. Fukuda, "Mechanical System Control with Man-Machine-Environment Interactions", [Proceedings of the 1993 IEEE International Conference on Robotics and Automation (1993) 239-244].
[2] 小菅一弘, 藤沢佳生, 福田敏男, "環境との相互作用が生じるマン・マシン系の制御", [日本機械学会論文集(C編) 59 (562) (1993) 1751-1756].

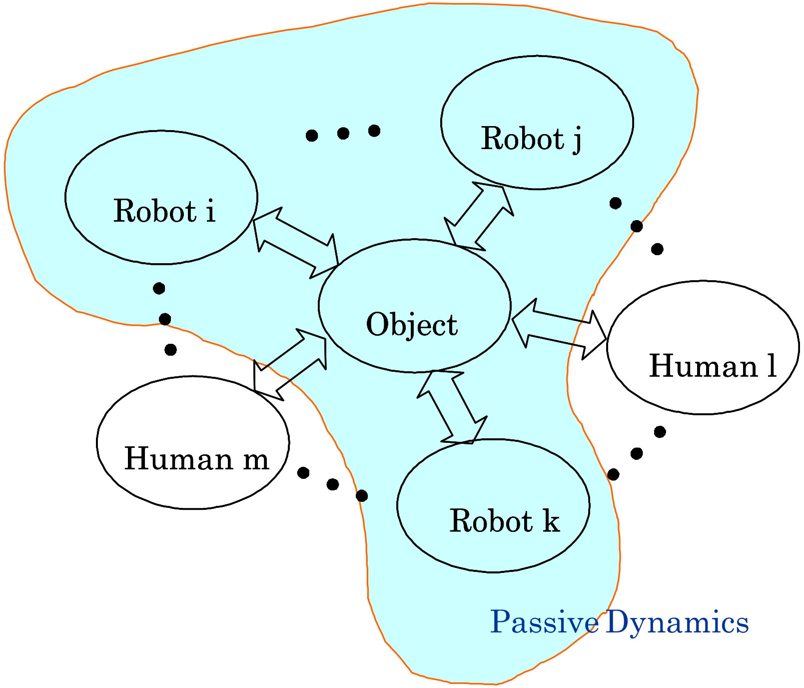
Robot Helpers





Human-Robot Cooperation
(Kosuge, 1993)

Robot Helpers



Stability Issues

Robot Helpers

MR Helper (Mobile Robot Helper, 1997~)

[1] K. Kosuge, M. Sato, ”Mobile Robot Helper”, [Proceedings of the 2000 IEEE International Conference on Robotics and Automation (2000) 583-588].
[2] 小菅一弘, 須田理央, 風村典秀, 佐藤学, 角谷啓, ”人と双腕型移動ロボット“MR Helper”による物体の協調搬送”, [日本機械学会論文集(C編) 69 (685) (2003) 84-90].

Robot Helpers

DR Helpers (Distributed Robot Helpers)

Y. Hirata, K. Kosuge, "Distributed Robot Helpers Handling a Single Object in Cooperation with a Human", [Proceedings of the 2000 IEEE International Conference on Robotics and Automations (2000) 458-463].

平田泰久, 初雁卓郎, 小菅一弘, 淺間一, 嘉悦早人, 川端邦明, "人間と複数の分散型ロボットヘルパ-との協調による単一物体の搬送", [日本機械学会論文集(C編) 68 (668) (2002) 181-188].

Robot Helpers

DR Helpers (Distributed Robot Helpers)

Y. Hirata, Y. Kume, Z. D. Wang, K. Kosuge, "Decentralized Control of Multiple Mobile Manipulators Based on Virtual 3-D Caster Motion for Handling an Object in Cooperation with a Human", [Proceedings of the 2003 IEEE International Conference on Robotics and Automation (2003) 938-943].

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Lessons Learned

MR Helper

DR Helper

Lessons Learned from Robot Helpers

- Some simple tasks, which could not be done by a human/humans, could be done with a robot helper(s).
- General tasks could not be done easily even with the assistive robot system(s), because the robot does not know how to collaborate with the human.


Lessons Learned from Robot Helpers

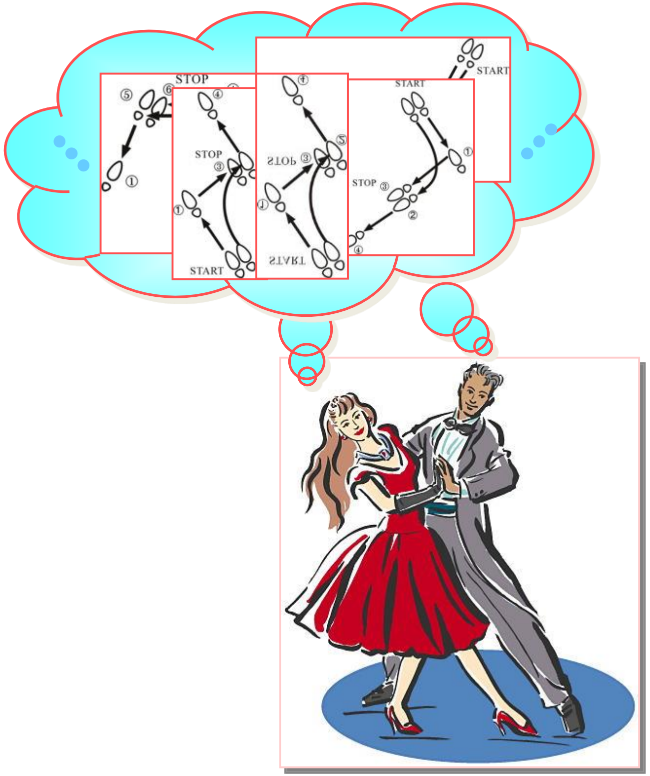
- In order to collaborate with the user, the robot has to know
  - the task,
  - its user’s intention,
  - how the user wants to be assisted
  - …

Dance Partner Robot

To develop a mechanism for closer human-robot coordination/interaction

Ballroom Dances

- A ballroom dance is performed by a dance couple, a male dancer and a female dancer.
- A dance consists of a set of figures of the dance.



Ballroom Dances

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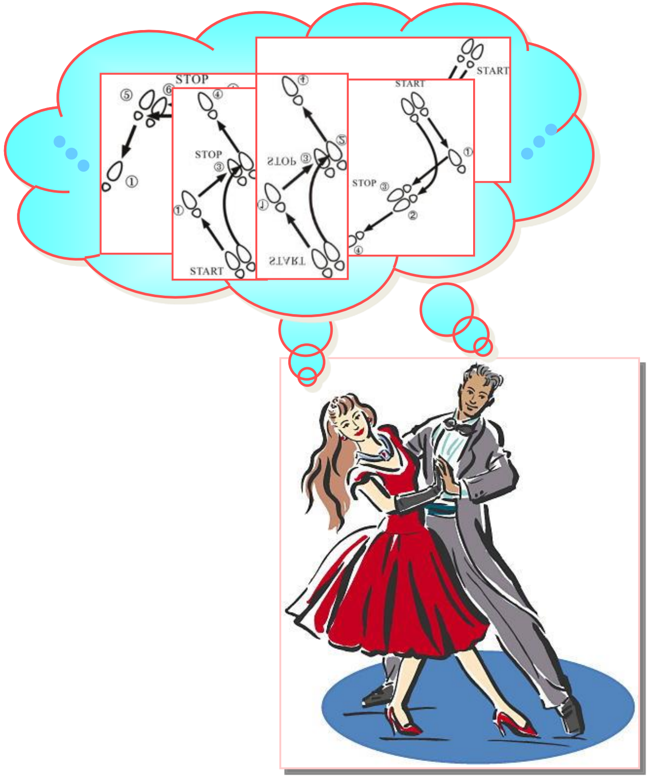
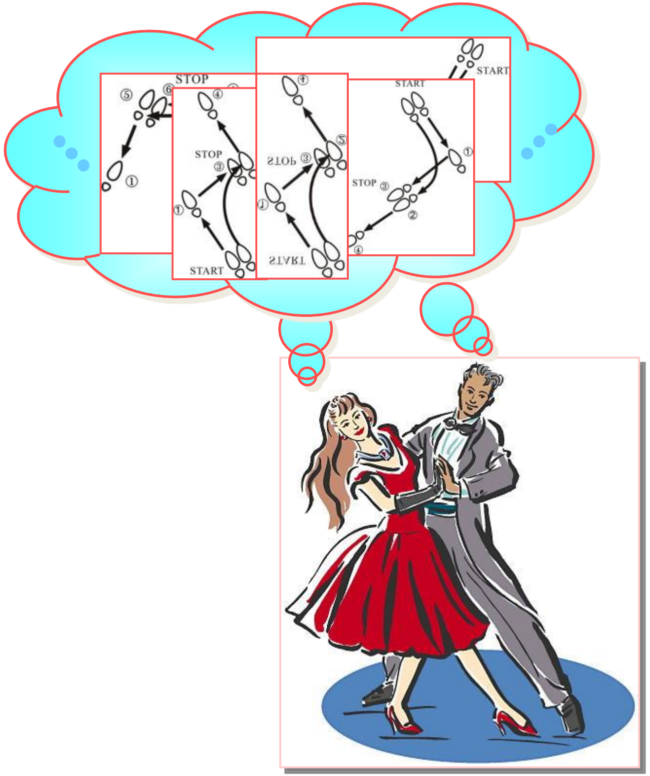
- The dance is lead by a male dancer.

  Which figure is coming next is controlled by the male dancer based on the rule of the dance and their surroundings.



Ballroom Dances

- The female dancer estimates the following figure at each figure transition through the interaction with the male dancer based on the knowledge of the dance.



Ballroom Dances

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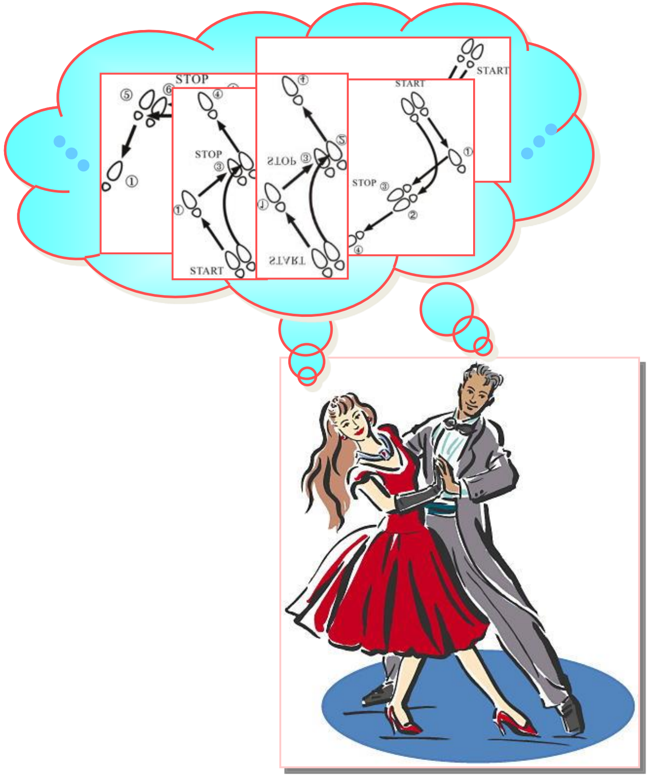
- The female dancer has to know the dance in order to dance with her partner:
  - The set of the dance figures.
  - The figure transition rule.
  - How to be lead by the male dancer or how to estimate the partner’s figure.

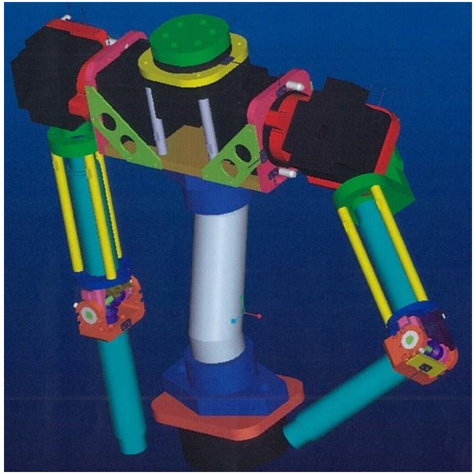


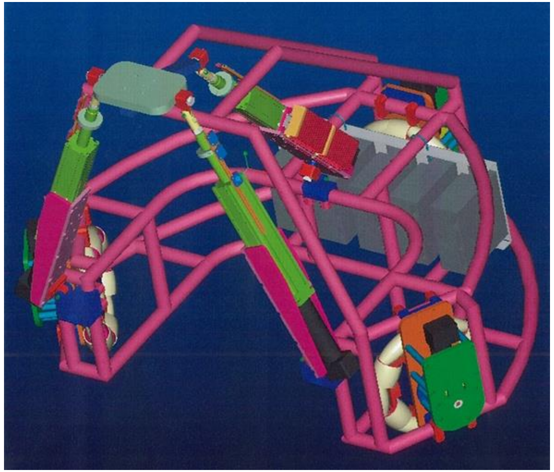
Dance Partner Robot "MS DanceR"

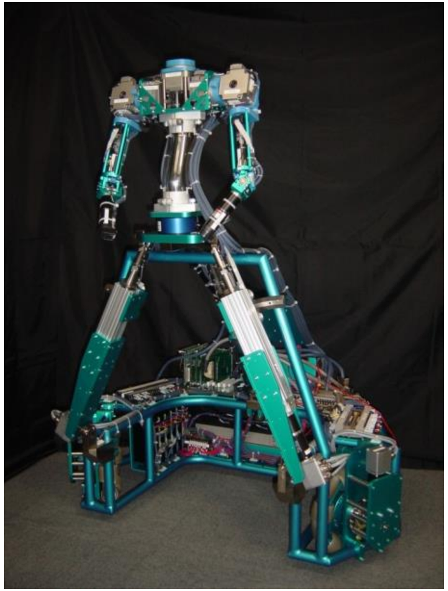
Aichi Expo

(March 24 ~ September 25, 2005)

Design of Robot Mechanism



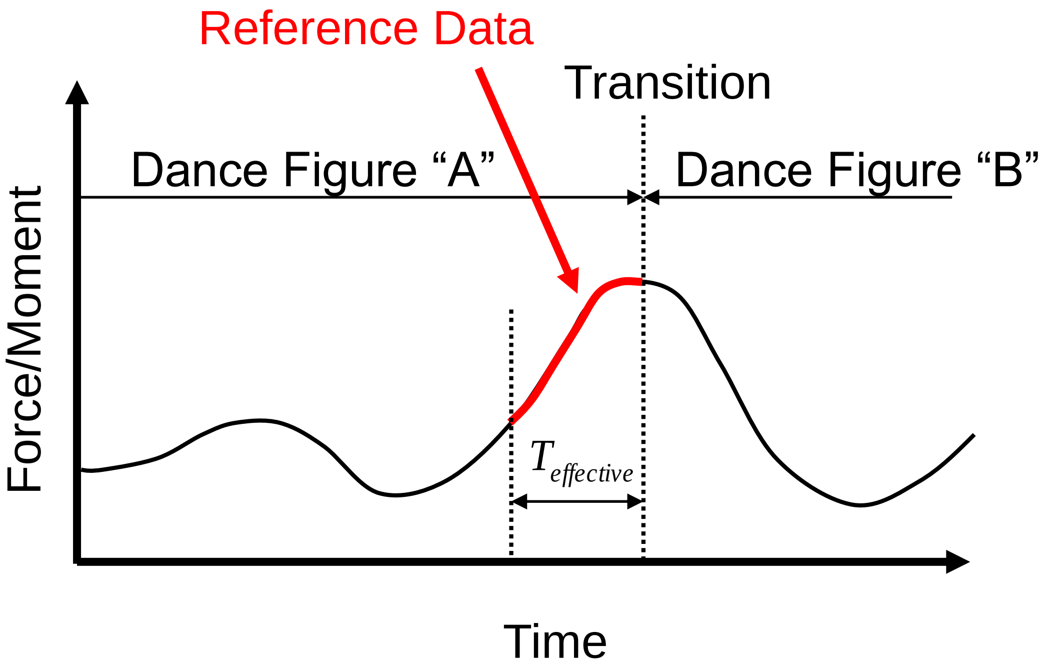




DoF: Neck : 1 Waist : 3
Arms : 4 x 2 Omni-directional mobile base : 3

Designed by Nomura Unison Co. Ltd. in cooperation with Tohoku University

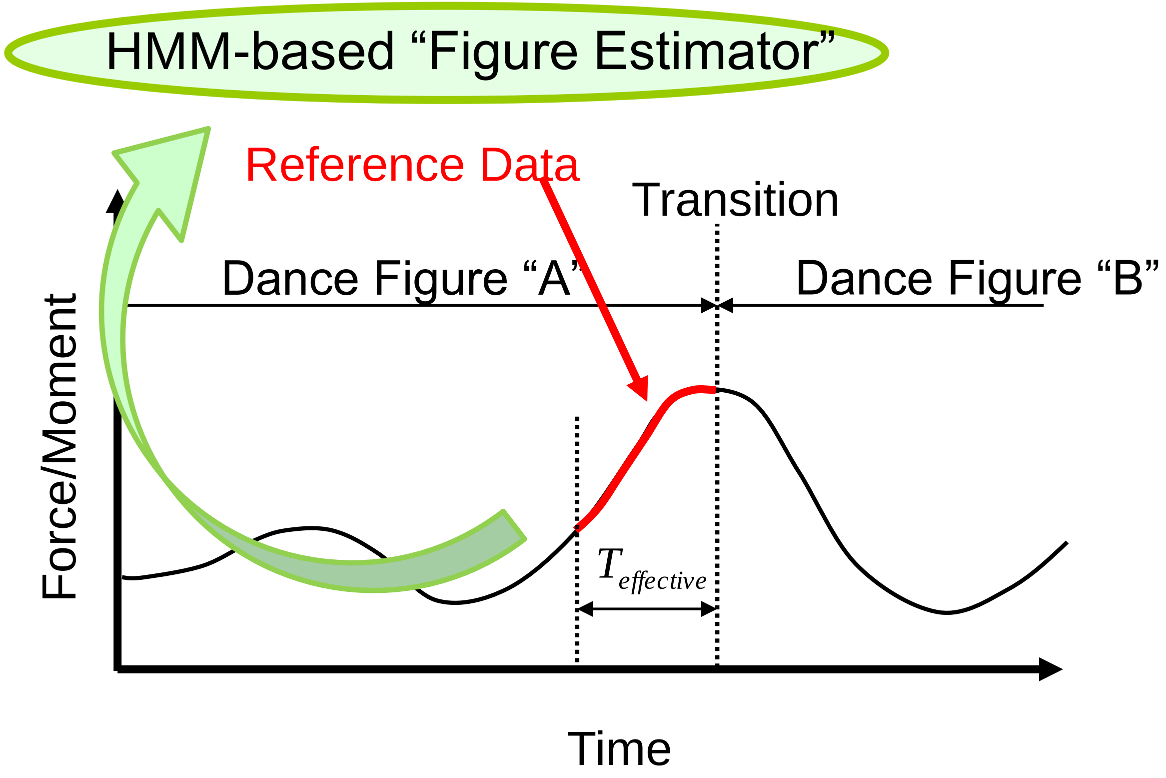
Sensory Data Used for Estimation



Time series data include uncertainty such as time-lag and variation because a dancer cannot always apply the same force/moment for each figure transition.

T. Takeda, K. Kosuge, Y. Hirata, "HMM-based Dance Step Estimation for Dance Partner Robot -MS DanceR-", [Proceedings of the 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems (2005) 1602-1607].

Sensory Data Used for Estimation



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Dance Partner Robot “PBDR”

PBDR as a Research Platform for Human-robot interaction

Dance Partner Robots

PBDR as a Research Platform for Physical Human-Robot Interaction

Dance Partner Robots

PBDR as a Research Platform for Physical Human-Robot Interaction

Dance Partner Robot

The Most Amazing Inventions

LEAD ON

A DANCING MACHINE

With a face modeled on Marilyn Monroe's and a long, flowing skirt to hide its three wheels, the Partner Ballroom Dance Robot is a 5-ft. 5-in. waltzing humanoid. Available in hot pink or blue, it has upper-body sensors that allow it to "predict" its partner's next steps. Dancing is just one application. "By interpreting users' movements to estimate what they want, care robots will be able to provide better service for the elderly who may be too sick or handicapped to give verbal orders," says bioengineering and robotics professor Kazuhiro Kosuge, one of the creators.

INVENTORS Tohoku University Nomura Unison Group, TroisO Co. Ltd.
AVAILABILITY Prototype only
TO LEARN MORE www.irs.mech.tohoku.ac.jp/top.html

TIME, NOVEMBER 21, 2005

Dance Partner Robot

Hold Me Closer, Tinny Dancer

These mechanical debutantes made their entrance last June at the prototype robot exhibition of the 2005 World Exposition, in Nagoya, Japan. The Partner Ballroom Dance Robots are the joint work of the Japanese robotics and machinery maker Nomura Unison Co., in Chino City, and the laboratory of Kazuhiro Kosuge at Tohoku University, in Sendai. Much of Kosuge's research involves getting robots to understand human intentions and to predict their actions. Just as a human dancer would, the robot reads its partner's next move by noticing the force and torque against its body. It looks up in its memory what that signal is likely to mean in the context of the dance it is performing and sends the correct motion commands to three motorized wheels hidden under its plastic dress.

Photo by Junko Kimura/Getty Images

16 IEEE Spectrum | September 2005 | INT www.spectrum.ieee.org

www.spectrum.ieee.org September 2005 | IEEE Spectrum | INT 17

Dance Partner Robot

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ジャパンデザイン
グッドデザインアワード・イヤーブック2007-2008
GOOD DESIGN AWARD YEAR BOOK 2007-2008

そのデザインに、引力はありますか？

$G = 6.67259 \times 10^{-11} m^3 \cdot s^{-2} \cdot kg^{-1}$

社交ダンスパートナロボット －PBDR－

人間の意図を推定して社交ダンスを踊るダンスパートナロボット

Partner Ballroom Dance Robot -PBDR-
Ar: Tohoku University + Nomura Unison, Co., Ltd. + TroisO, Co., Ltd.

人間の意図やその状態を推定することによって人間を適切に支援することのできるロボットシステムの実現を目指し，その一例として社交ダンスパートナロボットを開発した。

Ar：東北大学＋野村ユニソン(株)＋(株)トロワゾ
P：東北大学 大学院工学研究科 教授 小菅一弘
Dr：(株)トロワゾ 代表取締役 小此木達也
D：(株)トロワゾ 代表取締役 小此木達也

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Dance Partner Robot

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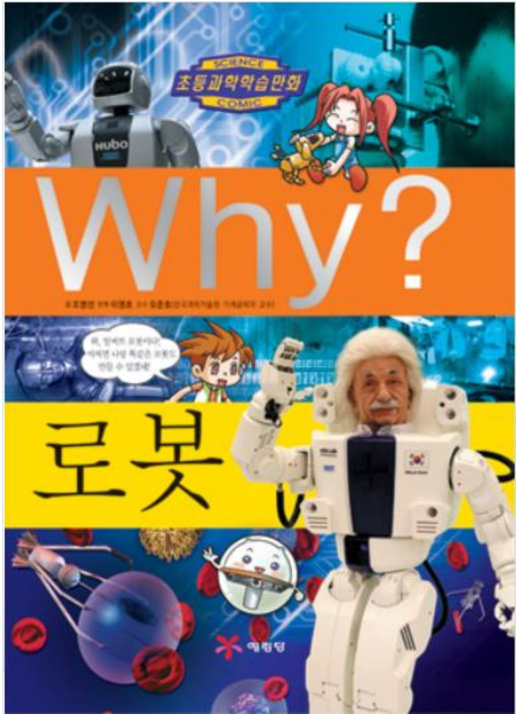
PBDR in Korea



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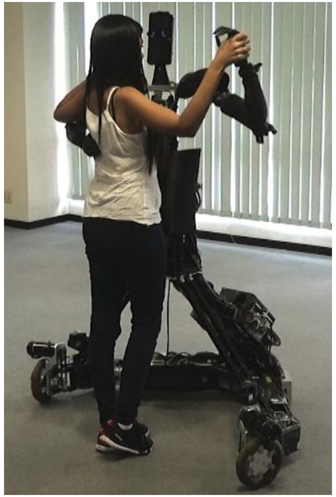

Challenges for Dance Partner Robots

- Stable physical interaction between a human and a robot
- Female Dance Partner Robot
  - Human behavior/intention estimation
    - How to read the its partner’s lead
- Male Dance Partner Robot
  - How to convey robot’s intention to its human partner
- Motion Entrainment
  - Based on Human modeling

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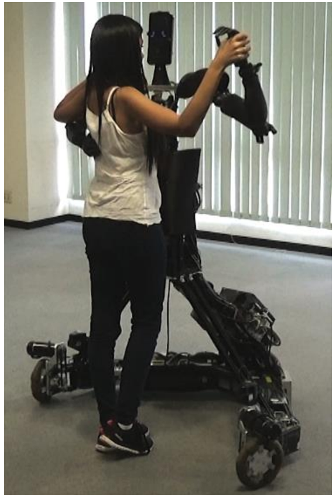
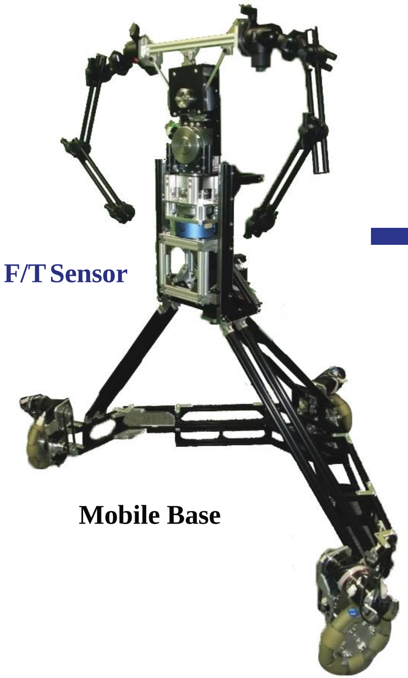
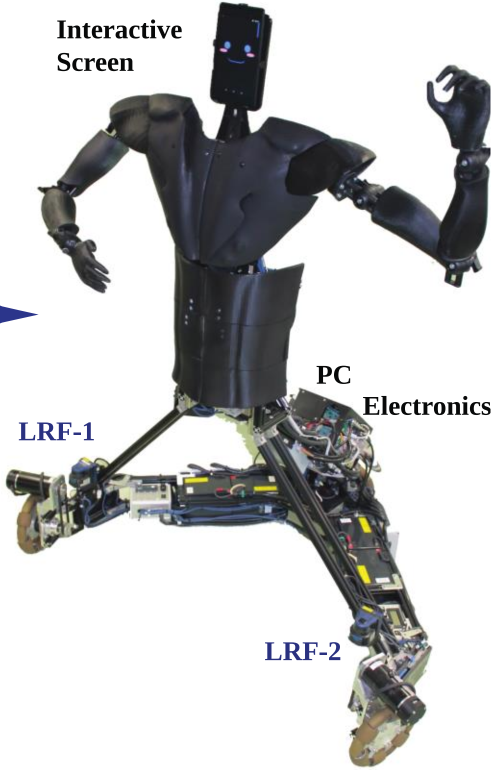


Robot Design

Mechanical Assembly



Whole Body Assembly



Motion Tests

Motion Analysis of Dancers

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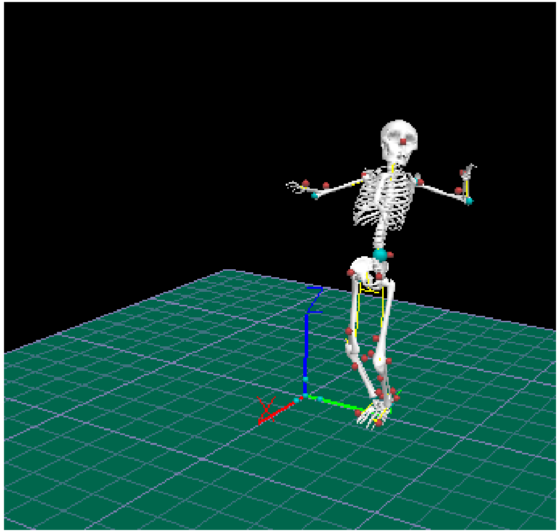
Analysis of the motions in dance using motion capture system:



An example of captured motions during the dance figure: closed change using commercially available software [1].

[1] Motion Analysis Corporation. (n.d.). Motion Analysis. Retrieved March 27, 2015, from http://www.motionanalysis.com/html/industrial/industrial.html

Motion Analysis of Dancers

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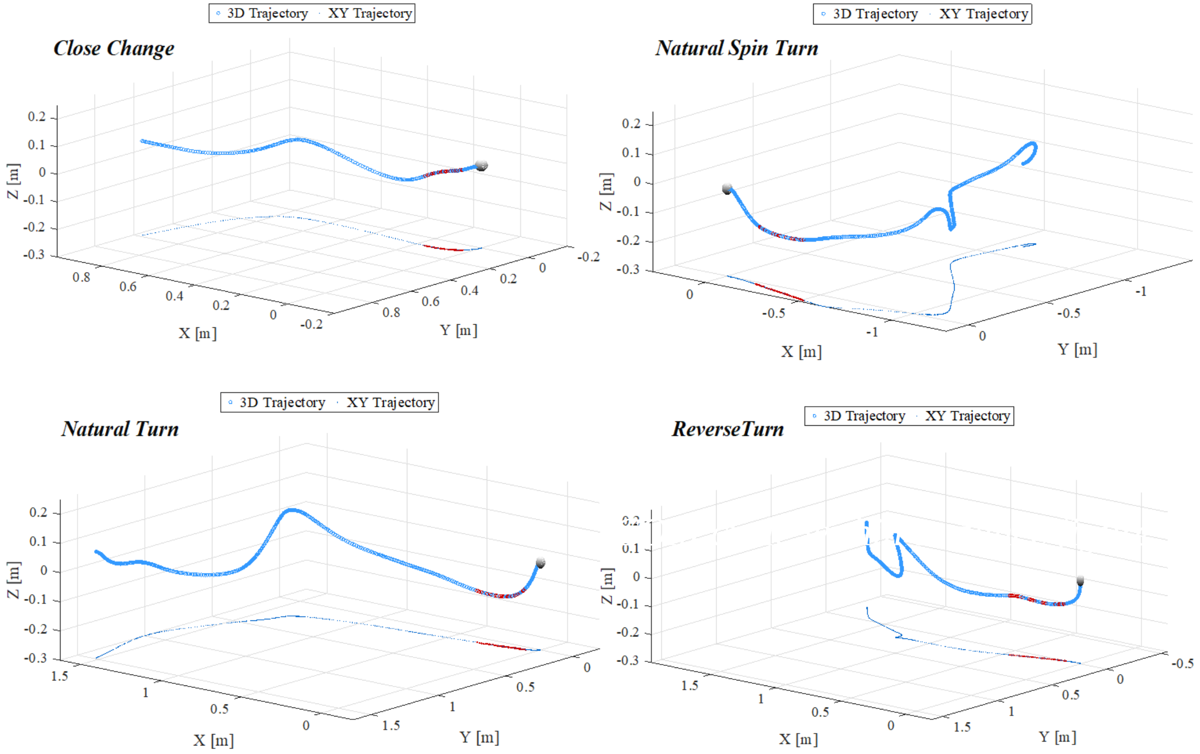
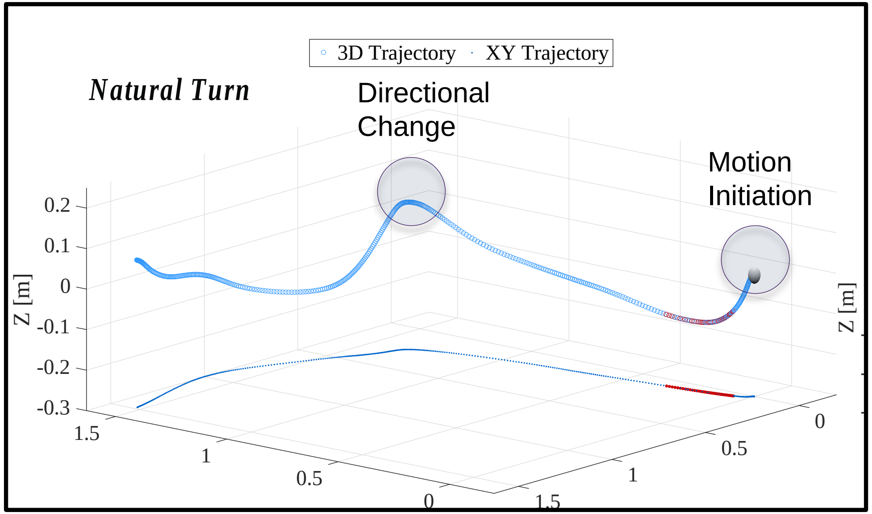
Example of four dance figures COM motions in 3D.



Motion Analysis of Dancers

- An example of COM Motions in 3D space

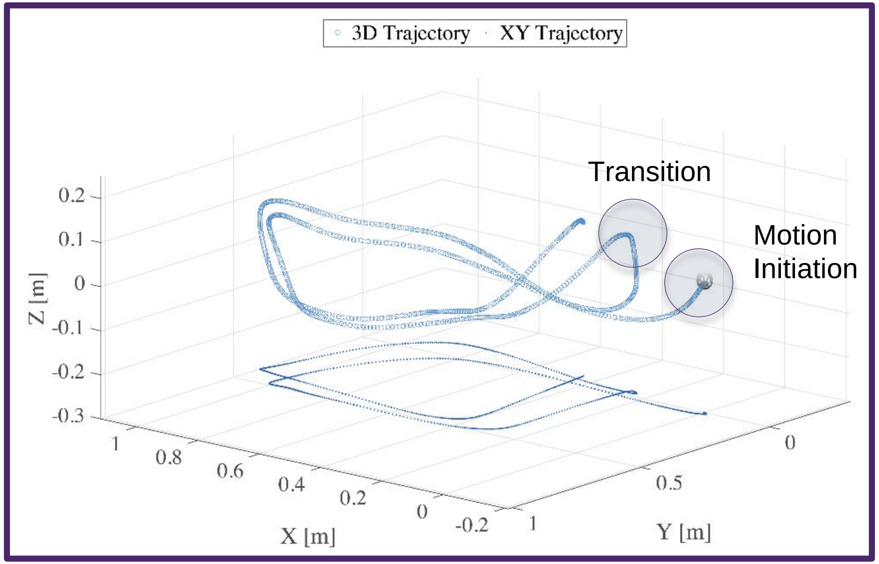


During a dance figure in Waltz, we observed that COM motions is related to

- Motion initiation.
- Directional changes.

Motion Analysis of Dancers

- An example of COM Motions in 3D space

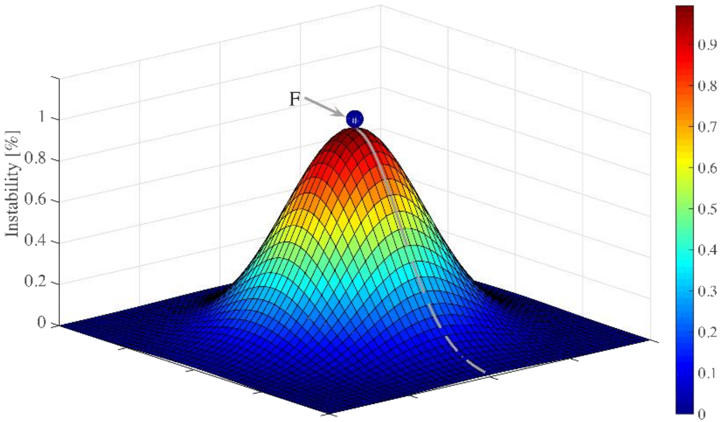


During the transitions of dance figures in Waltz, we also observed the similar pattern in COM motions relating to motion initiation and figure transition.

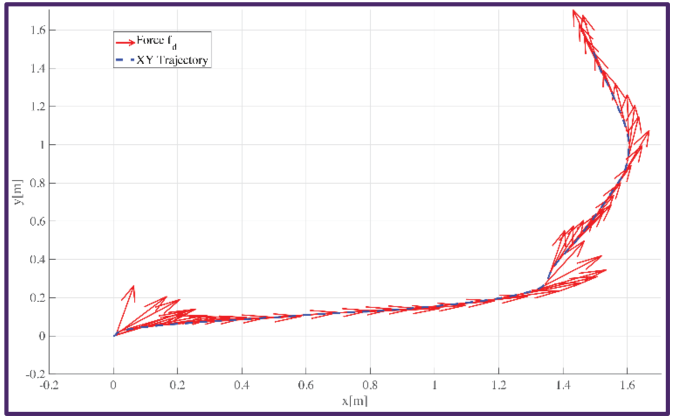
Leading the Partner by COM Motion

Guidance using COM motions through an unstable equilibrium point (G-UEP):

- Bringing the partner's COM to an unstable equilibrium point (UEP) by elevating the robot's COM during the physical interaction in the dance.
- Exerting a force in the desired motion direction.

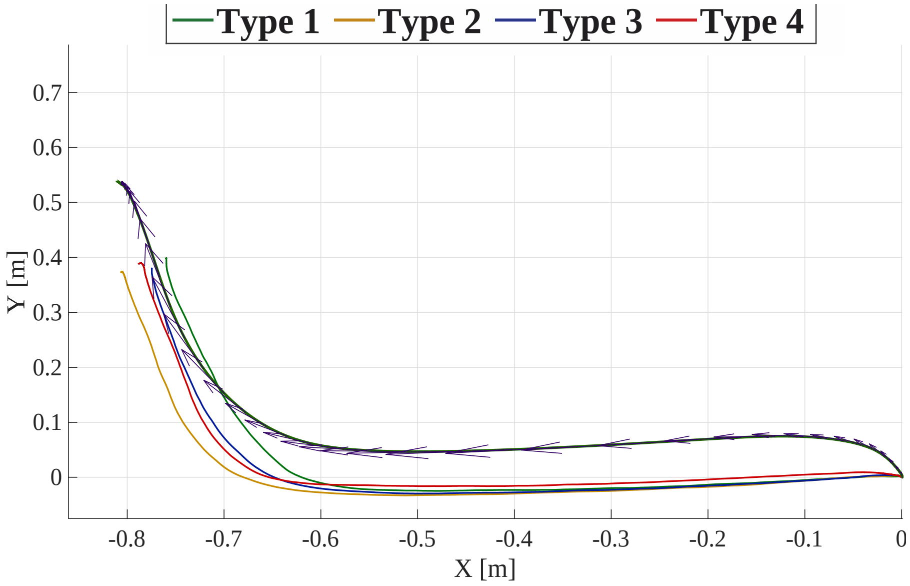


Unstable equilibrium point example.



Example of guidance
force along the dance

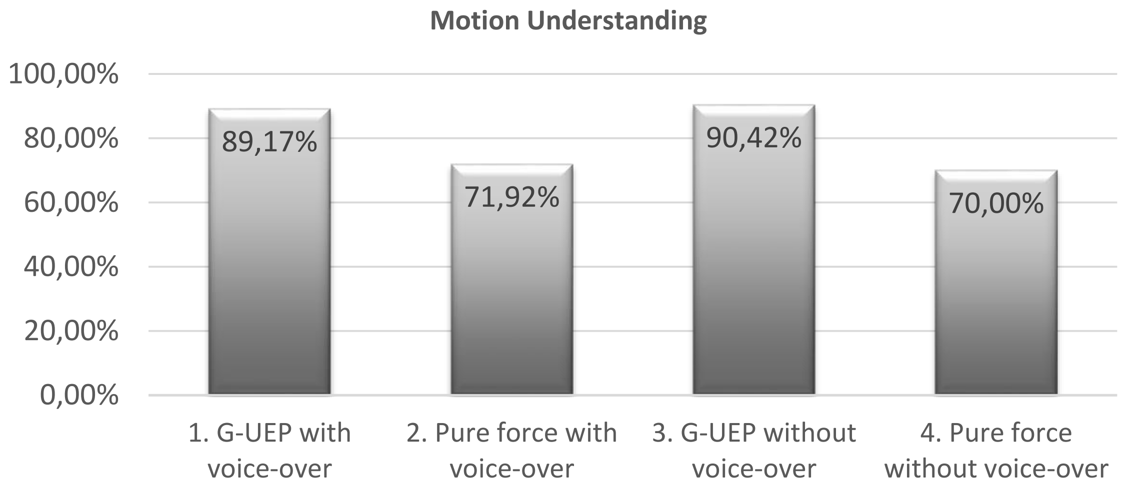
Evaluation of the Proposed Method



Example of trajectories achieved by a subject during the 4 types of test.

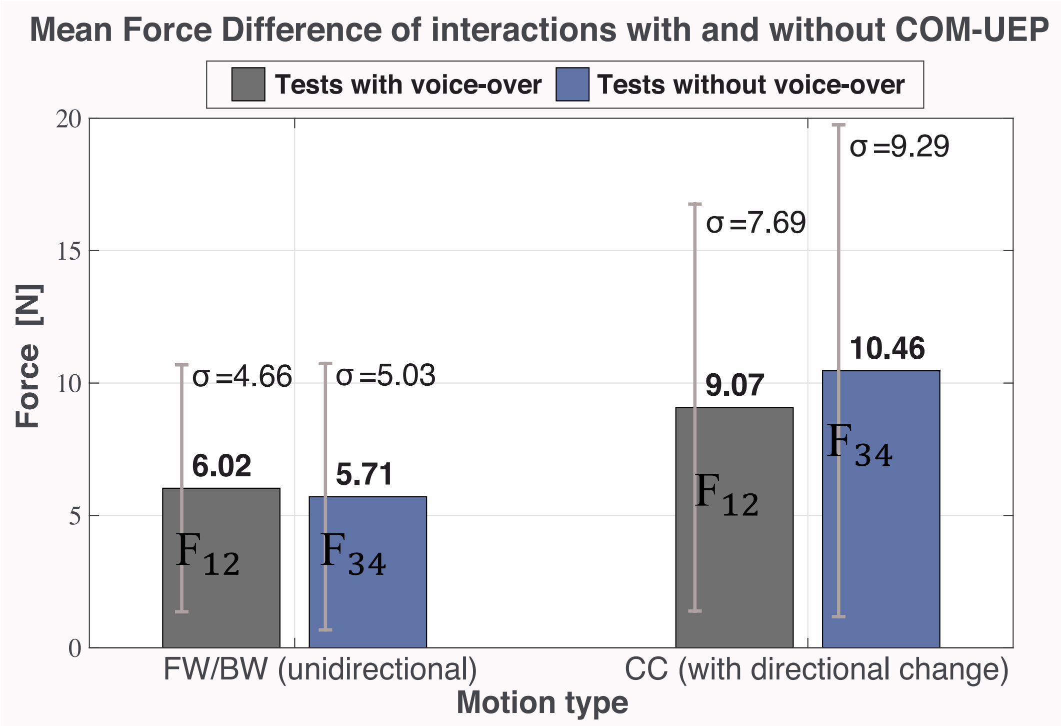
Example video of experiments with subjects.

Evaluation of the Proposed Method



- Understanding of robot's intention of motion was evaluated with the percentage of success in the motion (correct direction of motion).
  - G-UEP shows approximately 20% more motion direction understanding than pure force guidance.
  - Voice-over on interactions did not show difference in the motion understanding rate.

Evaluation of the Proposed Method



Significant reduction in interactions force was obtained by using the G-UEP.

Subjective Evaluation

Comfort: ”Emotional states which people have positive feelings during interactions such as relief, ease, and comfortable”.

Peace of Mind: ”Emotional states that reflects the opposite to negative feelings during interaction such as uneasiness and stress with the robots”.

Performance: Evaluative judgment about the robot’s ability to interact.

Controllability: Evaluative judgment about negative aspect regarding the interaction with the robot such as performing unanticipated actions, and harming humans.

Human-likeness: perceived similarity with humans in interactions.

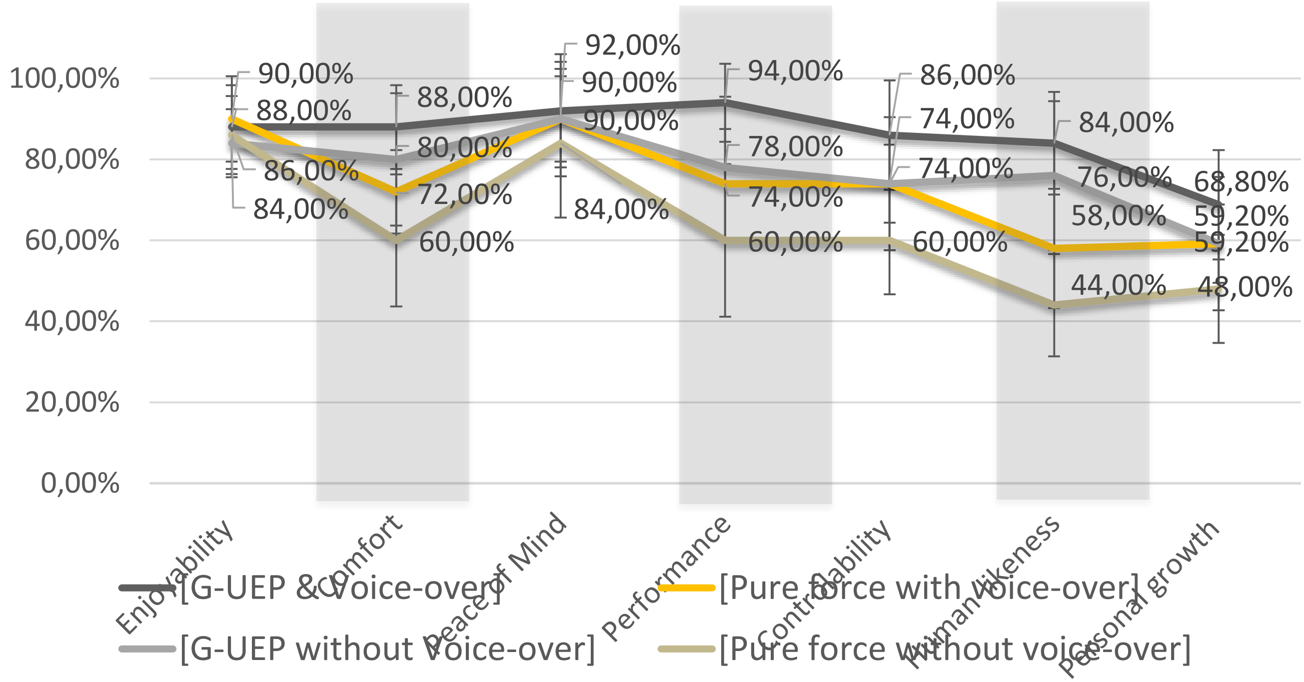
Enjoyability: self-evaluated level of enjoyment during the dance.

Personal Growth: perceived personal improvement in the dance.

Kamide, H., Kawabe, K., Shigemi, S., & Arai, T. (2015). Anshin as a concept of subjective well-being between humans and robots in Japan. *Advanced Robotics*, *29*(24), 1624–1636.

Subjective Evaluation

Significant difference was obtained in factors of Comfort, Performance, and Human-likeness.



Progressive Teaching

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- The progressive teaching (PT) methodology is proposed based on Piagets theory of cognitive development states.

”Knowledge is constructed based on experiences related to mental, biological and physical stage of the development”. [1]

[1] L.-D. Hammond, K. Austin, and S. Orcutt, “How People Learn,” Stanford University, Tech. Rep., 2001.

Proposed methodology:

1. Assessment of the skill based on the current stage of physical development.

2. Feedback of the assessed skill performance for enhancing skill model formation.

3. Physical feedback based on skill performance.

Diego Felipe Paez Granados, Breno A. Yamamoto, Hiroko Kamide, Jun Kinugawa, and Kazuhiro Kosuge, “Dance Teaching by a Robot: Combining Cognitive and Physical Human–Robot Interaction for Supporting the Skill Learning Process”, IEEE Robotics and Automation Letters, Voo.2, pp.1452 - 1459, 2017

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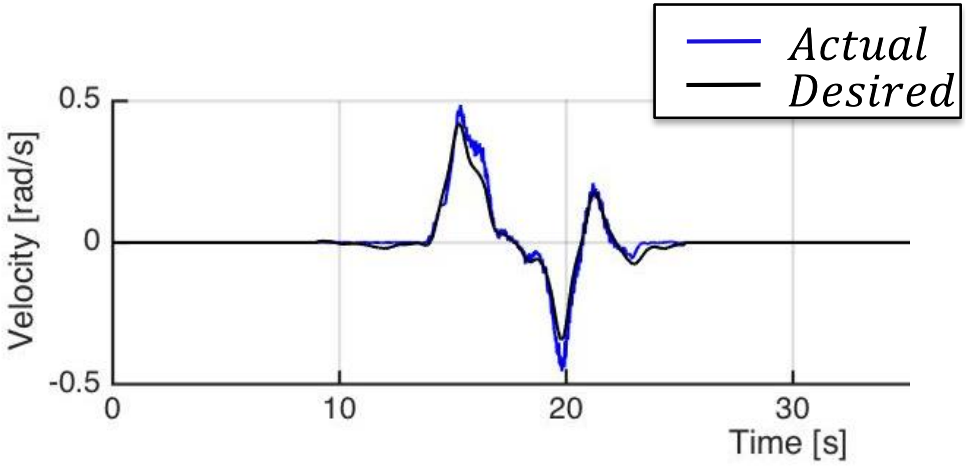
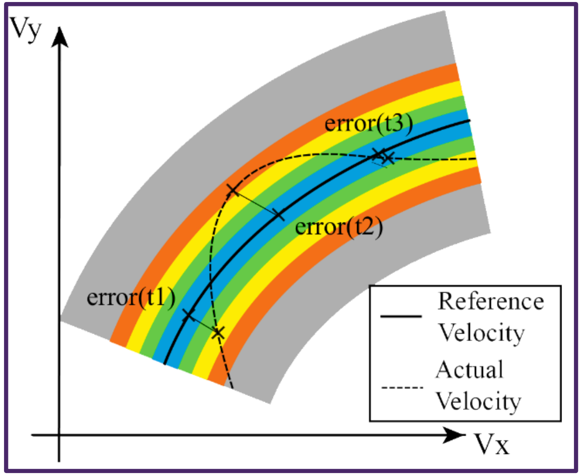
Skill Assessment of Dance





- Analysis of the skill in the velocity profile permits a better assessment for any user.
- Skill is assessed based on mean squared error of velocity calculated as follows:

$$E\left(k\tau\right) = \sum_{n=1}^{n_{dof}} e_n\left(k\right) W_n$$

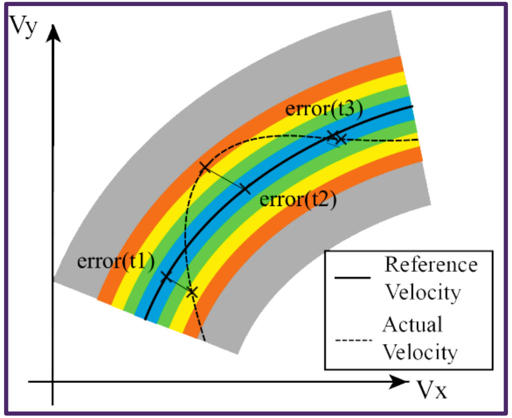
- Where $e_n = \sqrt{\left(\dot{X}_{dn}(k\tau) - \dot{X}_n(k\tau)\right)^2}$ represents the error and W_n represent a $n\ x\ n$ weighing matrix.

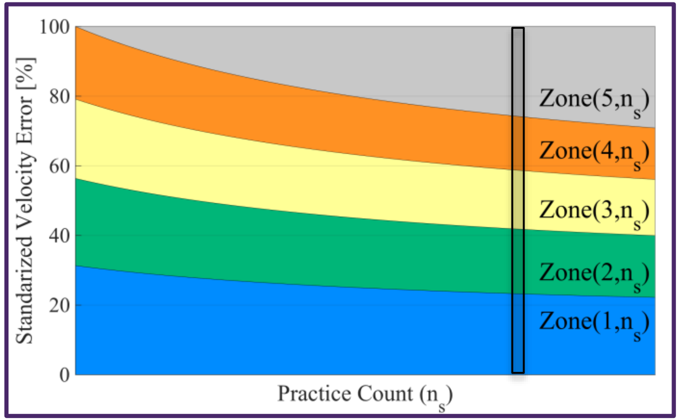
Diego Felipe Paez Granados, Breno A. Yamamoto, Hiroko Kamide, Jun Kinugawa, and Kazuhiro Kosuge, "Dance Teaching by a Robot: Combining Cognitive and Physical Human–Robot Interaction for Supporting the Skill Learning Process", IEEE Robotics and Automation Letters, Voo.2, pp.1452 - 1459, 2017

Skill Assessment of Dance

Skill assessment is carried out based on score zones.
Current stage is assumed proportional to practices' count:

- Generous scoring for novice dancers.
- Severe scoring for experienced dancers.





$$Zone\left(x, n_s\right) = c_3 \left(\frac{1}{c_2 n_s + 1} + 1\right) \left(\frac{1}{x + c_1}\right)$$

Diego Felipe Paez Granados, Breno A. Yamamoto, Hiroko Kamide, Jun Kinugawa, and Kazuhiro Kosuge, "Dance Teaching by a Robot: Combining Cognitive and Physical Human–Robot Interaction for Supporting the Skill Learning Process", IEEE Robotics and Automation Letters, Voo.2, pp.1452 - 1459, 2017

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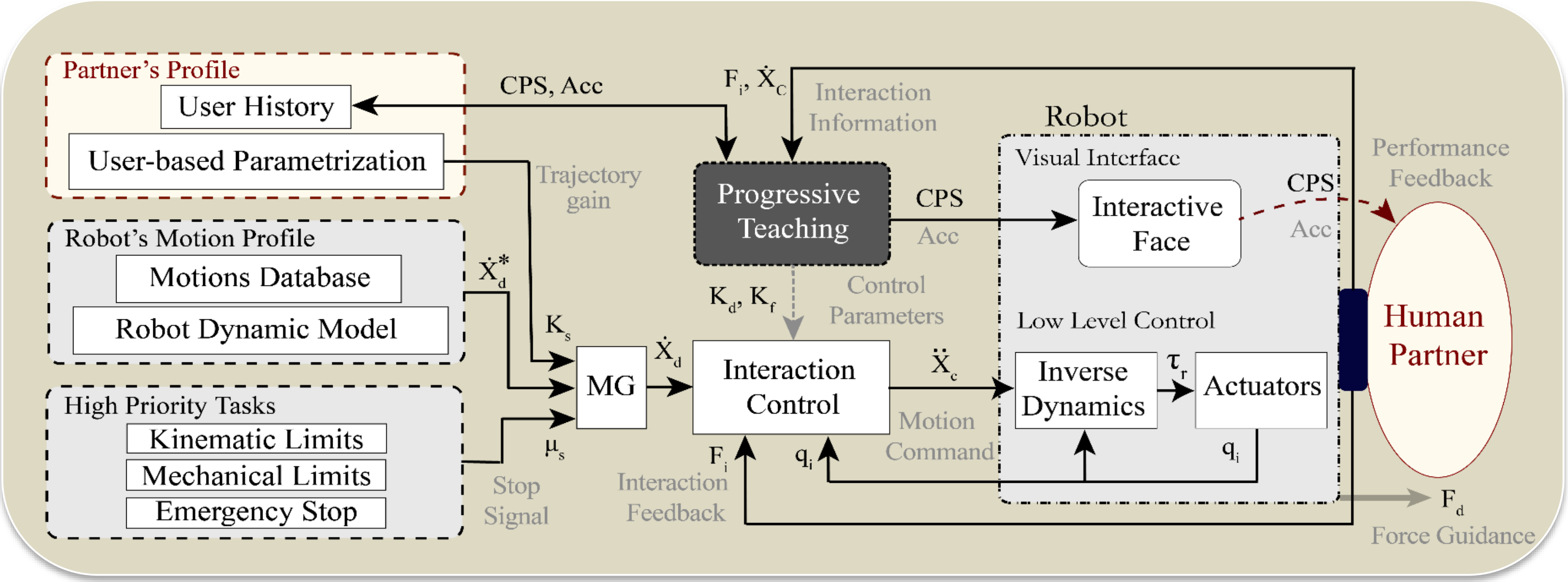
Progressive Teaching

Combining cognitive and physical interaction for enhancing the skill learning.



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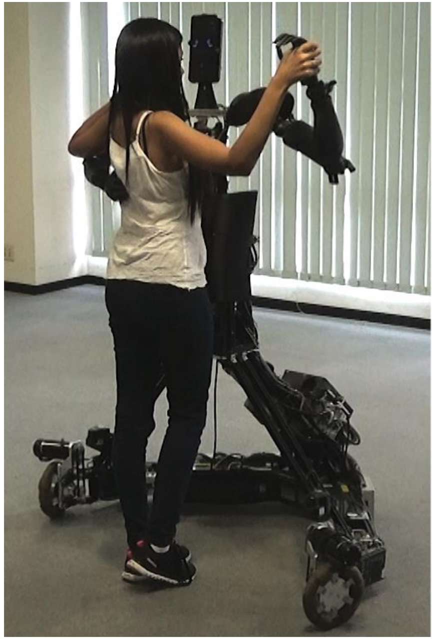
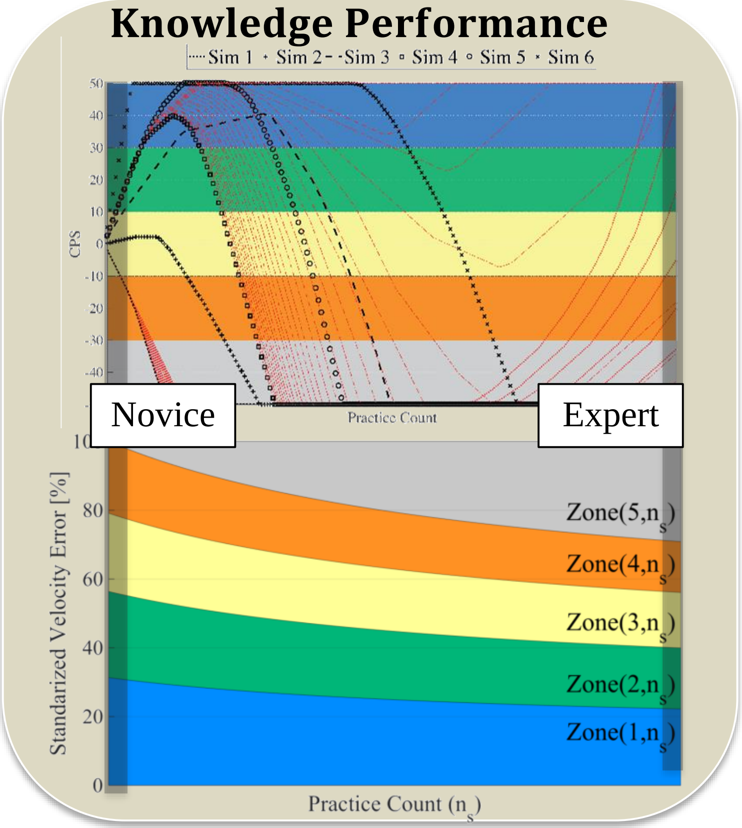
Progressive Teaching

The robot gives feedback of the current state through CPS in color scales.





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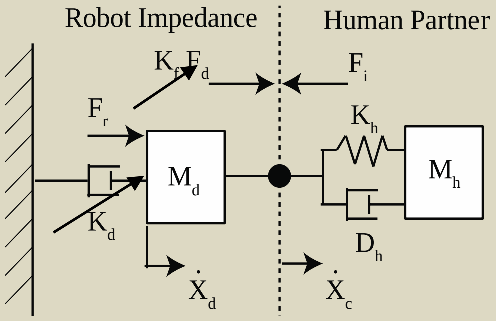
Adaptive Interaction Control

Low-level controller model



$$\ddot{X}_c = \ddot{X}_d + M_d^{-1}\left(K_d\left(\dot{X}_d - \dot{X}\right) - K_f F_d - F_i\right)$$

$K_d - Damping\ Gain$

$M_d - Desired\ Impedance\ Inertial\ Matrix$

$K_f - Interaction\ ForceError\ gain$

$K_h - Human\ \ Stifness$

$\widetilde{F}_i - Estimated\ Interation\ Force$

$D_h - Human\ \ Damping$

Modifying the robot’s impedance, so that, for low CPS values would produce higher damping and guidance force and high CPS would decrease both damping and force.

Diego Felipe Paez Granados, Breno A. Yamamoto, Hiroko Kamide, Jun Kinugawa, and Kazuhiro Kosuge, “Dance Teaching by a Robot: Combining Cognitive and Physical Human–Robot Interaction for Supporting the Skill Learning Process”, IEEE Robotics and Automation Letters, Voo.2, pp.1452 - 1459, 2017

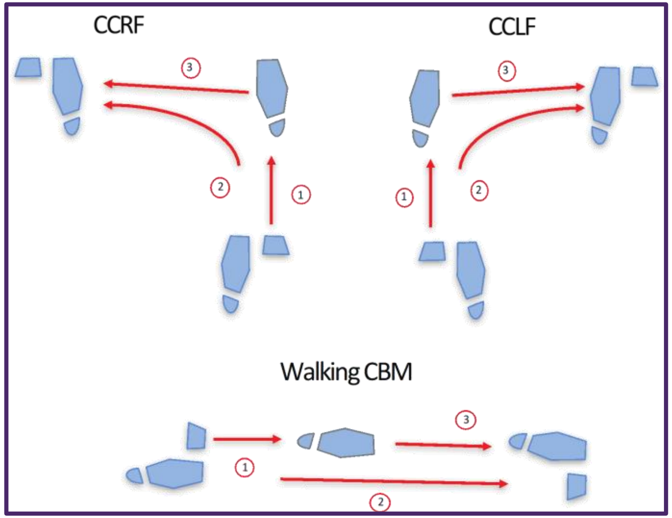
Adaptive Interaction Control

- Enhancing the perceived safety and trust in the robot during interactions through the usage of a limiting interaction force.
- For beginners level the maximum f_d has been settled to 60 N.

Diego Felipe Paez Granados, Breno A. Yamamoto, Hiroko Kamide, Jun Kinugawa, and Kazuhiro Kosuge, “Dance Teaching by a Robot: Combining Cognitive and Physical Human–Robot Interaction for Supporting the Skill Learning Process”, IEEE Robotics and Automation Letters, Voo.2, pp.1452 - 1459, 2017

Evaluation of Progressive Teaching

- User-based Configurations:
  - 12 Users: 6 Constant Dynamics (non-adaptive impedance control) and 6 users with the proposed adaptive PT controller.
  - 50% female and 50% male.
  - 6 types of dance figures:



Evaluation of Progressive Teaching

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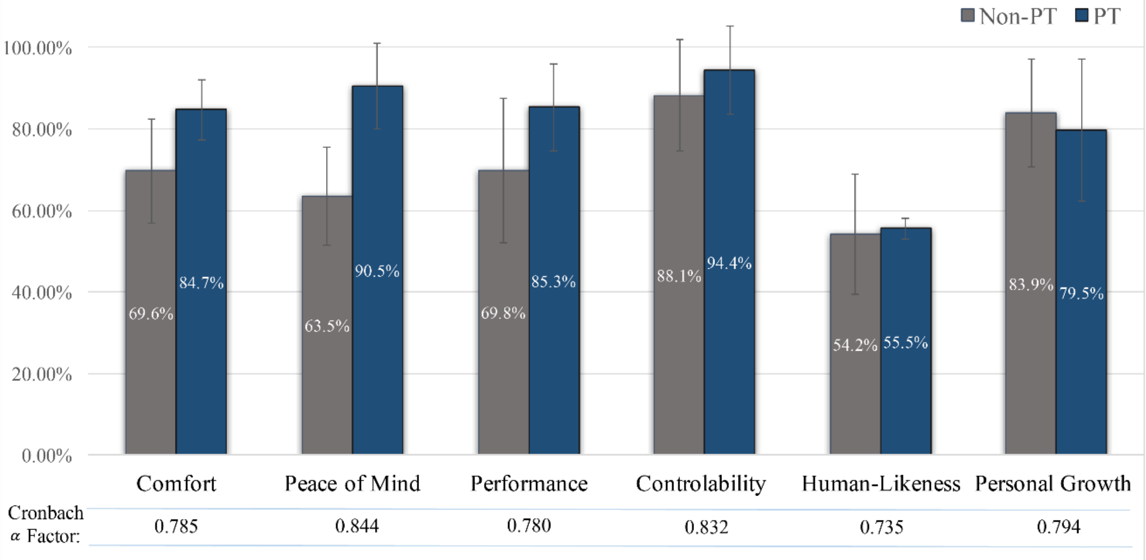
Subjective evaluation [1] among trainings: 12 subjects



Significant difference at the $p < .01$level for the two training conditions was found for Comfort, Peace of mind, and Performance factors.

CPS: Cumulative Performance Score

[1] Kamide, H., Kawabe, K., Shigemi, S., & Arai, T. (2015). Anshin as a concept of subjective well-being between humans and robots in Japan. *Advanced Robotics*, *29*(24), 1624–1636.

RoboDANTE (Robot DANce TEacher)

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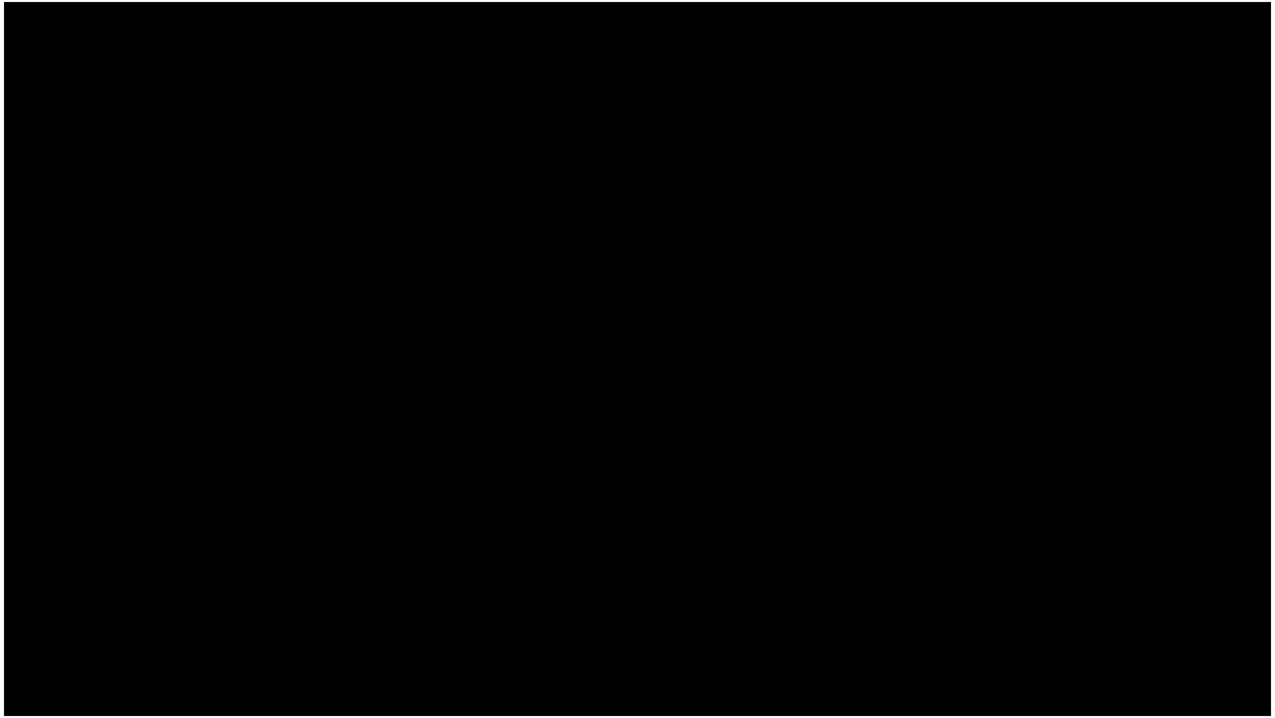


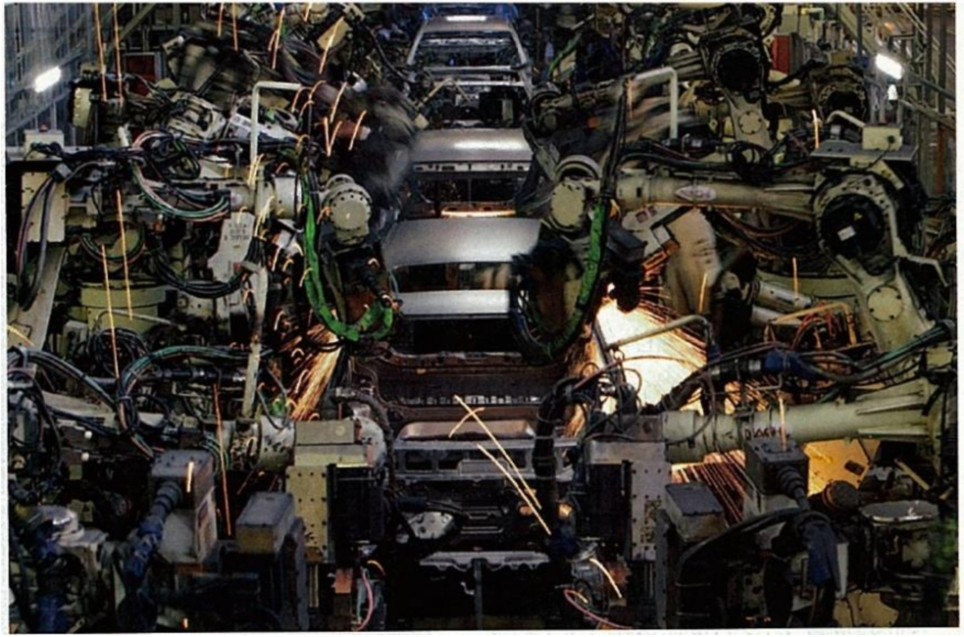
http://spectrum.ieee.org/automaton/robotics/robotics-hardware/video-friday-robot-dance-teacher-transformer-drone-pneumatic-reel-actuator

RoboDANTE (Robot DANce TEacher)

Outline

- Challenges and Opportunities of Robotics
  - Overview of Robotics (by JST in 2009)
- Examples of Physical Human-Robot Interaction
- Dance Partner Robots
  - MS DanceR and PBDR
  - RoboDANTE
- PaDY
  - PaDY in a factory
- Conclusions

Automobile Factories



Welding Process

Industrial robots have played important roles in manufacturing industries, especially in automobile factories.

Automobile Factories

Assembly Process
http://response.jp/issue/2004/0120/article57131_1.images/61053.html

There are many non-automated processes.

- Industrial robots are not suitable for tasks that require dexterous human skills, tasks in unstructured environment, etc.

Automobile Assembly Line

- A sequence of the tasks, necessary parts/tools for each task, and when and where each task is performed are scheduled a priori for each type of the car produced.
- During the work, the worker needs to return to a work bench with parts and tools several times to pick up necessary parts/tools.

Automobile Assembly Line

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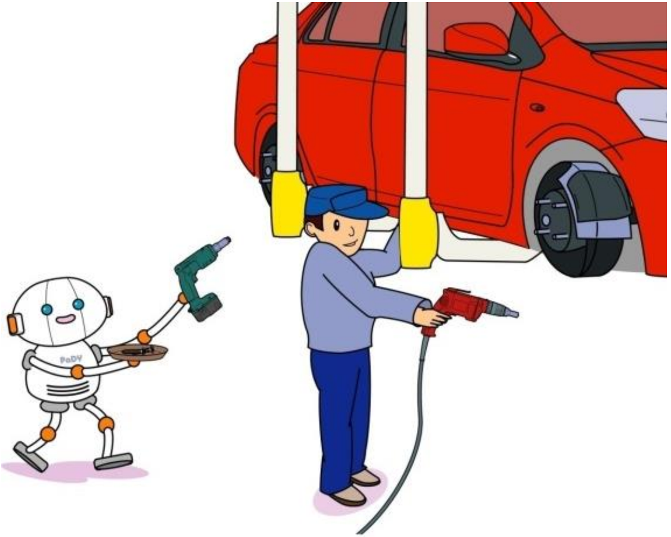
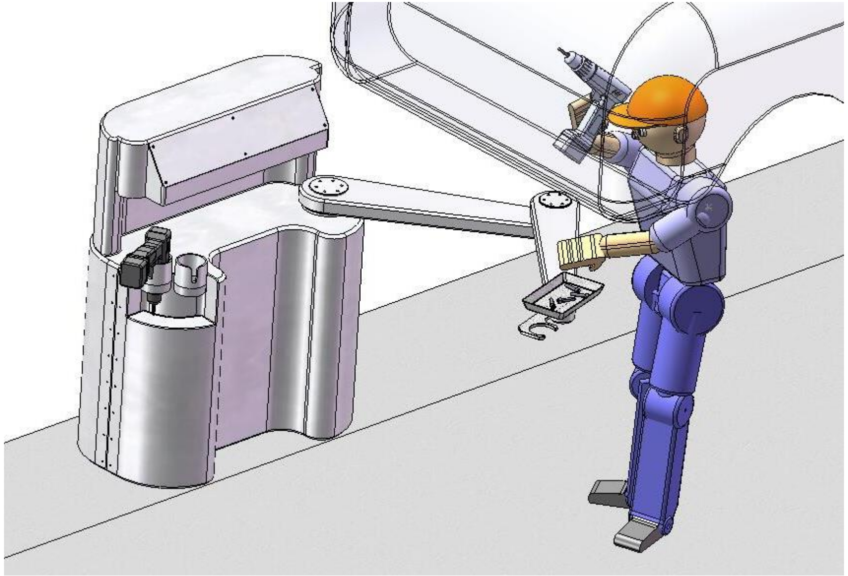


- If a robot could provide the worker with necessary parts and tools when he/she needs them, the worker could concentrate on the assembly tasks.

[1] 衣川潤，川合雄太，菅原雄介，小菅一弘，“組立作業支援パートナロボットPaDY（第1報，コンセプトモデルの開発とその制御）”，[日本機械学会論文集，C編,77(783),(2011),4204-4217]
[2] J. Kinugawa, Y. Kawaai, Y. Sugahara and K. Kosuge, “PaDY：Human-Friendly/Cooperative Working Support Robot for Production Site”, [The 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems Proceedings,(2010),5472-5479].

Co-worker Robot “PaDY”

- **PaDY is a robot which delivers necessary parts and tools to a worker when he/she needs them.**
  - to reduce the worker’s load
  - to improve efficiency of the work
  - to prevent mistakes of the work
  - etc.



“in-time Parts/tools Delivery to You” robot

[1] 衣川潤，川合雄太，菅原雄介，小菅一弘，“組立作業支援パートナロボットPaDY（第1報，コンセプトモデルの開発とその制御）”，[日本機械学会論文集，C編,77(783),(2011),4204-4217]

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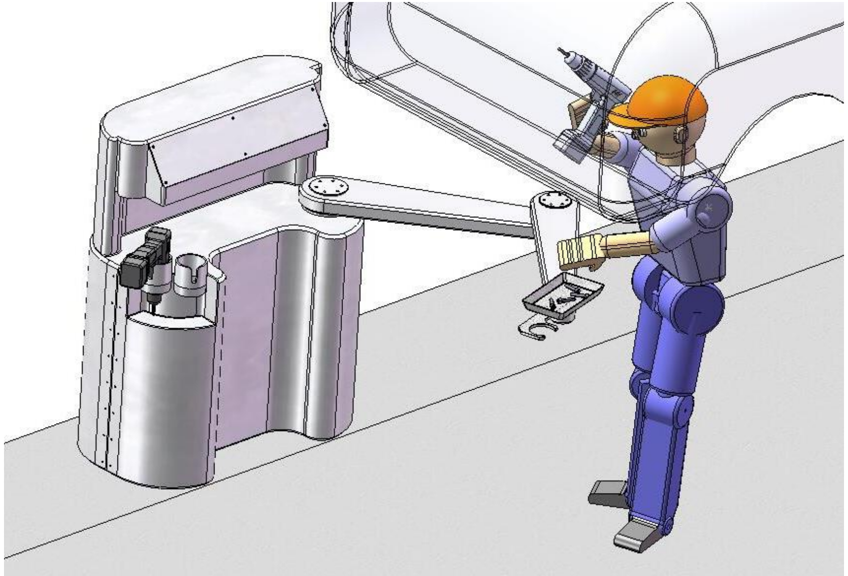
Co-worker Robot "PaDY"

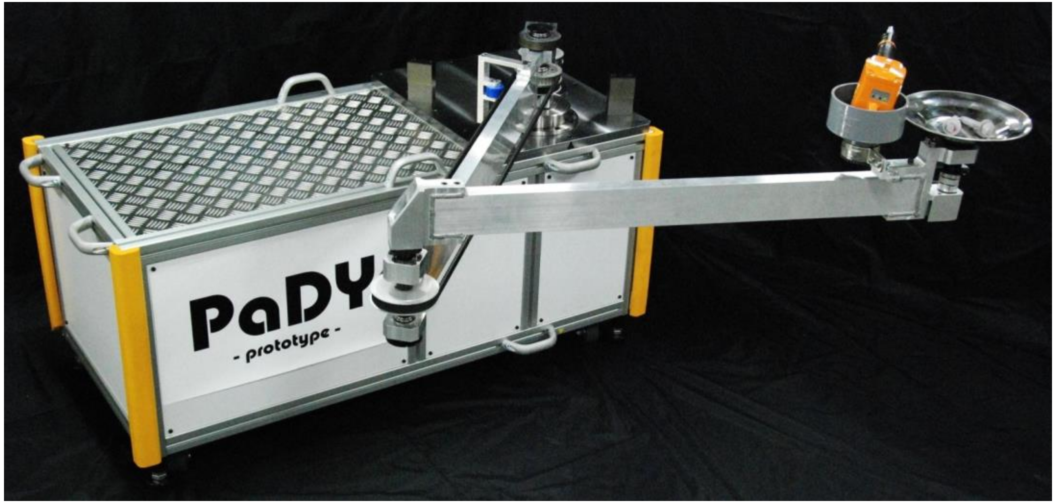
- In order to deliver parts/tools to a place, where the worker needs them, when the worker needs them without disturbing the worker's work, the robot needs to know
  - the task,
  - its user's intention,

  and
  - how the user want to be assisted



"in-time Parts/tools Delivery to You" robot

The First Prototype of PaDY (P1)



Size : (W) 1370 × (D)590 × (H) 1035[mm]
Link Mechanism : Horizontal Articulated Robot
Maximum Reach : 2.0 [m] (1st Link Length : 1168[mm], 2nd Link Length : 982[mm])
Weight of Working Parts : 11.5[kg]
Maximum Load : 3 [kg]
Range of Movement : 1st Joint : 200[deg], 2nd Joint : 360[deg]
Actuator : 1st Joint & 2nd Joint : DC Servo Motor 80[W], 3rd Joint : DC Servo Motor 15[W]

Evaluation Experiment

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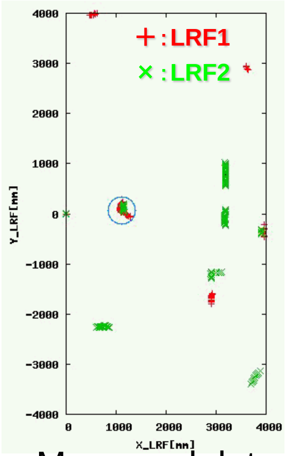
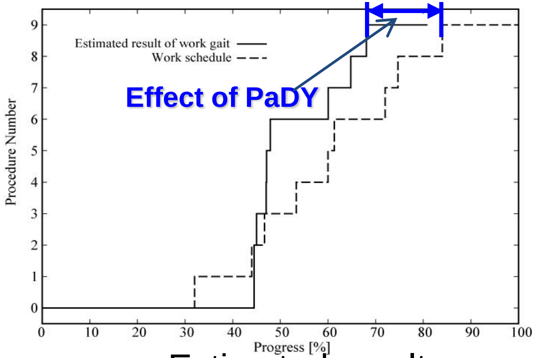


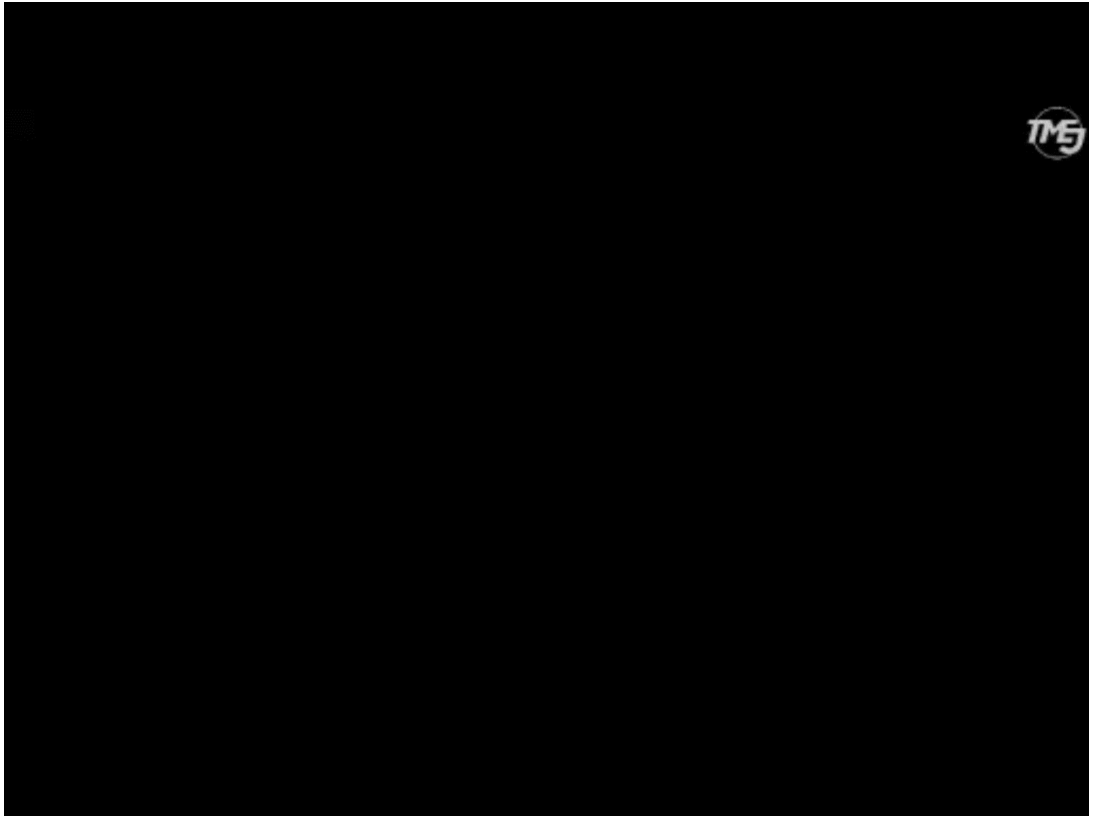
Measured data



Estimated result

The worker's motion necessary for picking parts/tools has been reduced.
The worker could finish his tasks earlier than the work schedule.

Factory Installation



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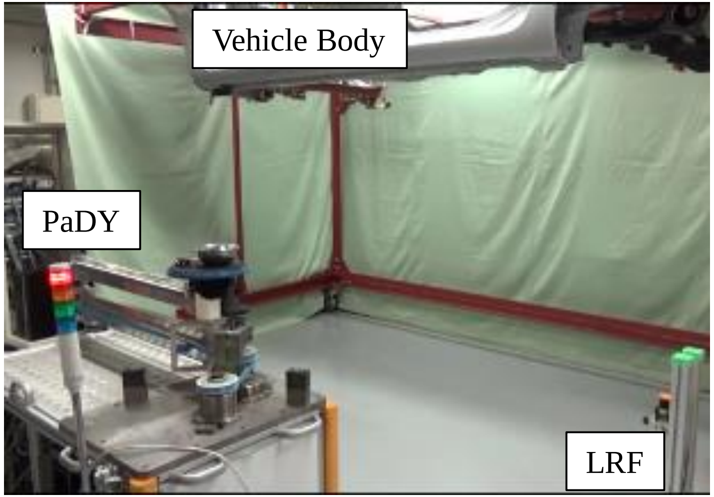
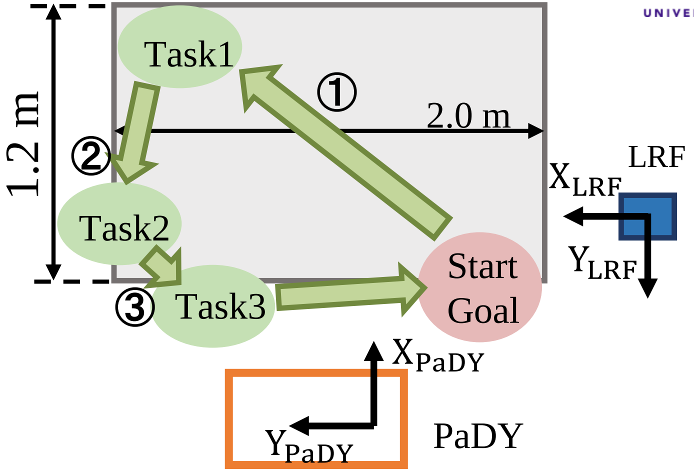
Improved Worker's Behavior Estimation





- A subject is requested to do three tasks.
- After the three tasks were finished, the probabilistic model is updated.

Jun Kinugawa, Akira Kanazawa, Shogo Arai, and Kazuhiro Kosuge, "Adaptive Task Scheduling for an Assembly Task Coworker Robot Based on Incremental Learning of Human's Motion Patterns", IEEE Robotics and Automation letters, Vol. 2, No. 2, pp.856-863, 2017

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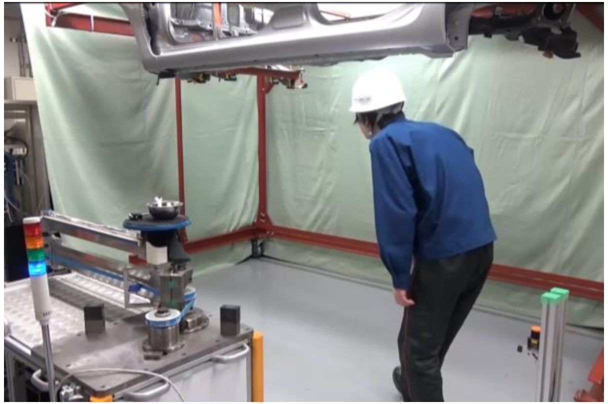
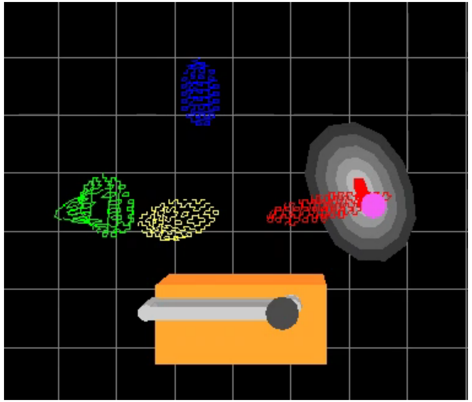
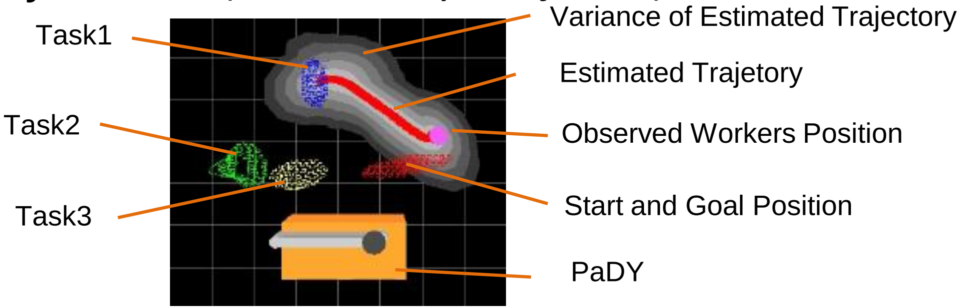




Ordinary Motion (10th trial by Subject A)



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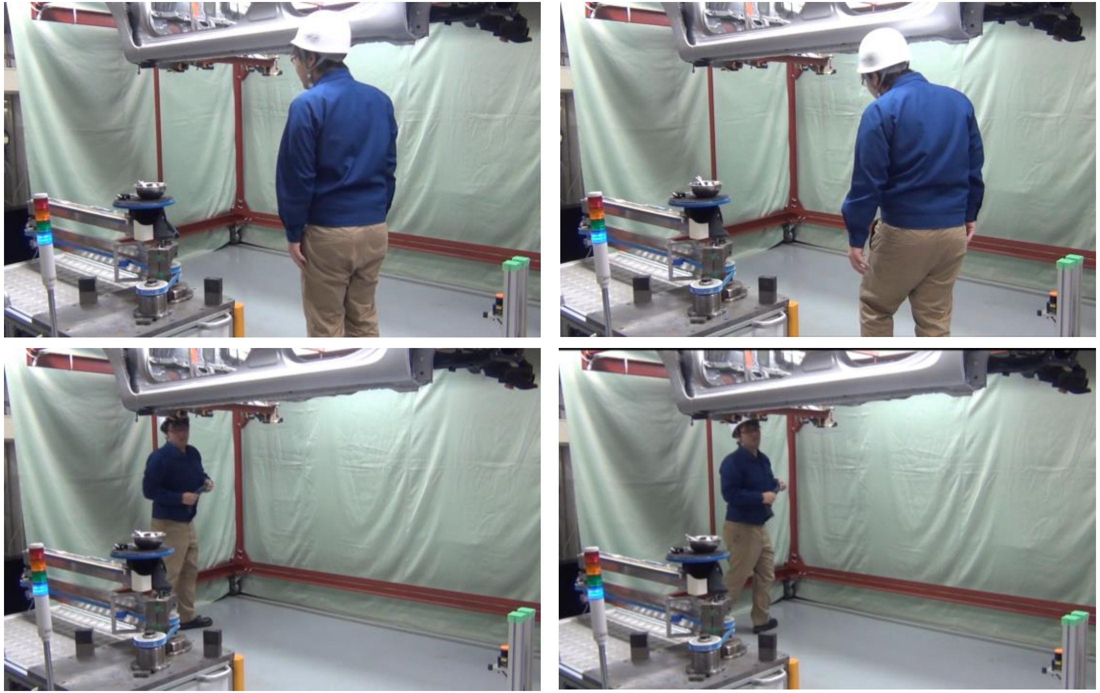
Improved Worker’s Behavior Estimation

trial 1 （without estimation） trial 10 （with estimation）

Start ⇒ Task1

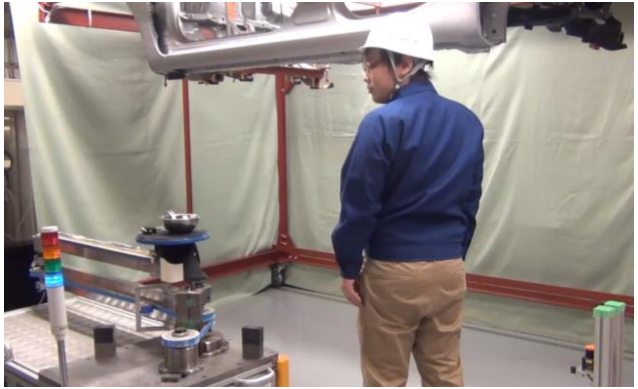
Task1 ⇒ Task2

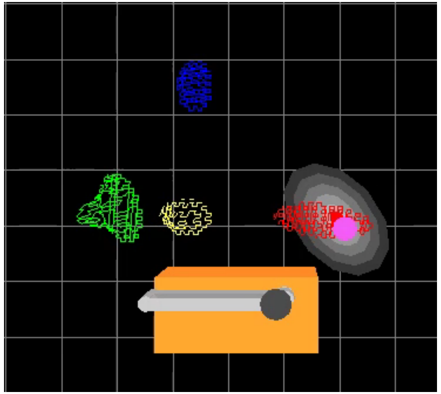


Comparison of the work by subject B

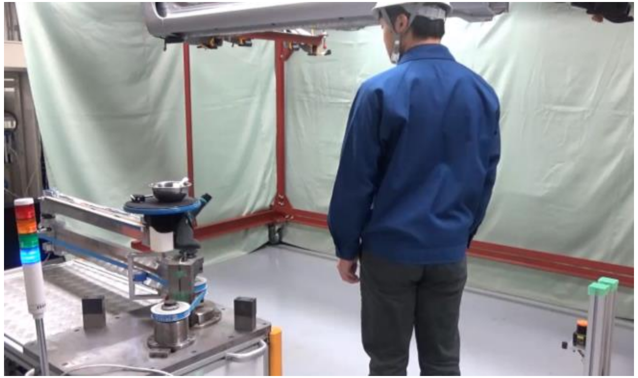
Jun Kinugawa, Akira Kanazawa, Shogo Arai, and Kazuhiro Kosuge, “Adaptive Task Scheduling for an Assembly Task Coworker Robot Based on Incremental Learning of Human’s Motion Patterns”, IEEE Robotics and Automation letters, Vol. 2, No. 2, pp.856-863, 2017

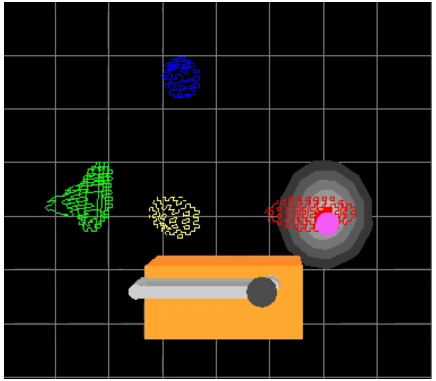
Improved Worker's Behavior Estimation





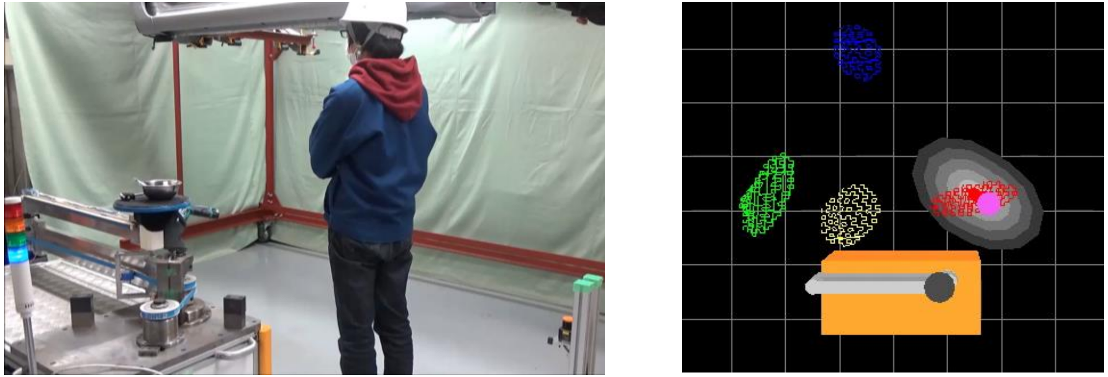
Subject B, Irregular 3



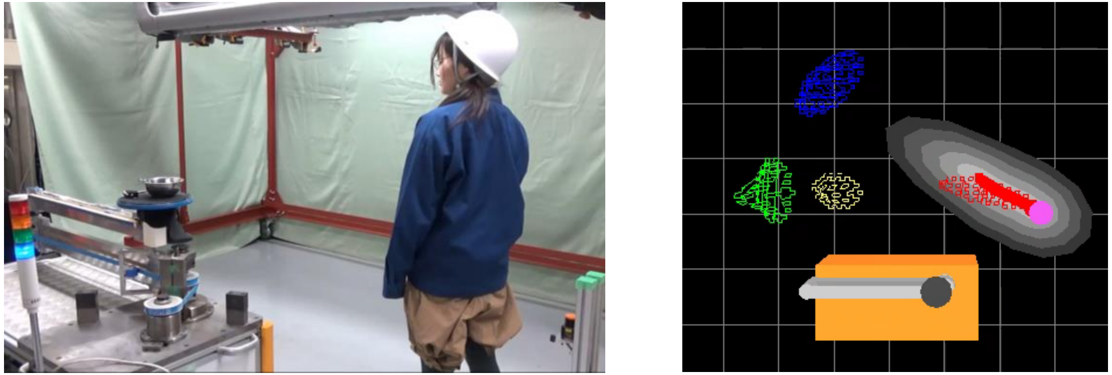


Subject C, Irregular 1

Improved Worker's Behavior Estimation

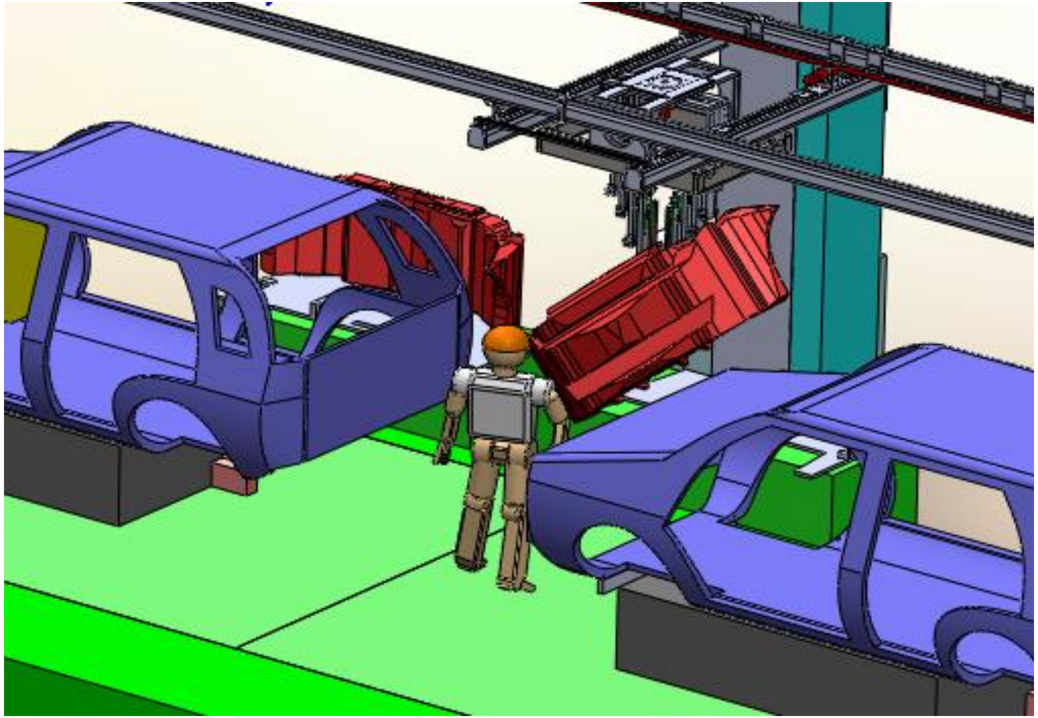


Subject D, Irregular 3



Subject E, Irregular 1

B-PaDY



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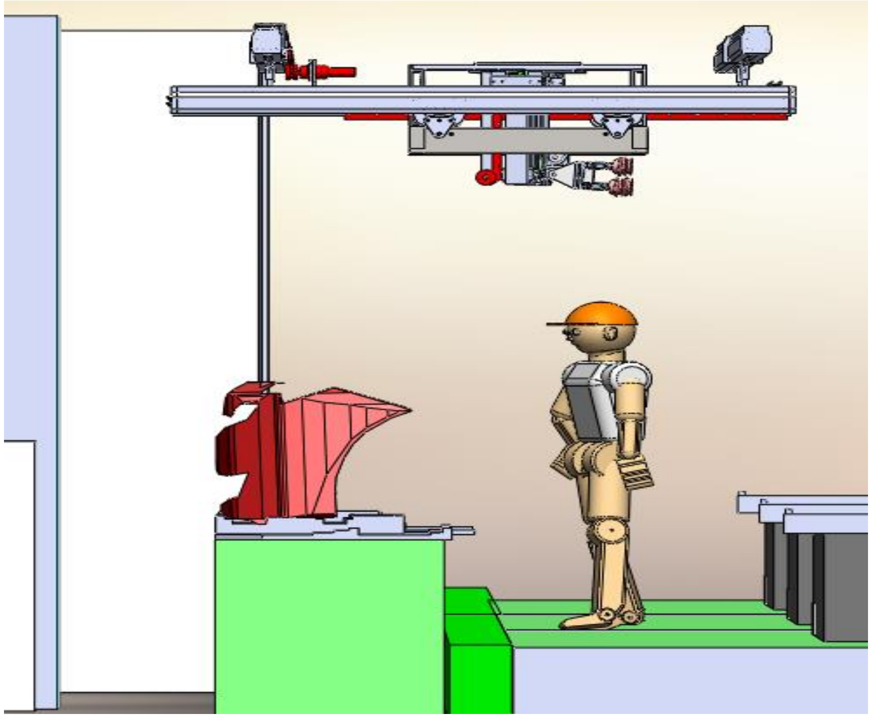

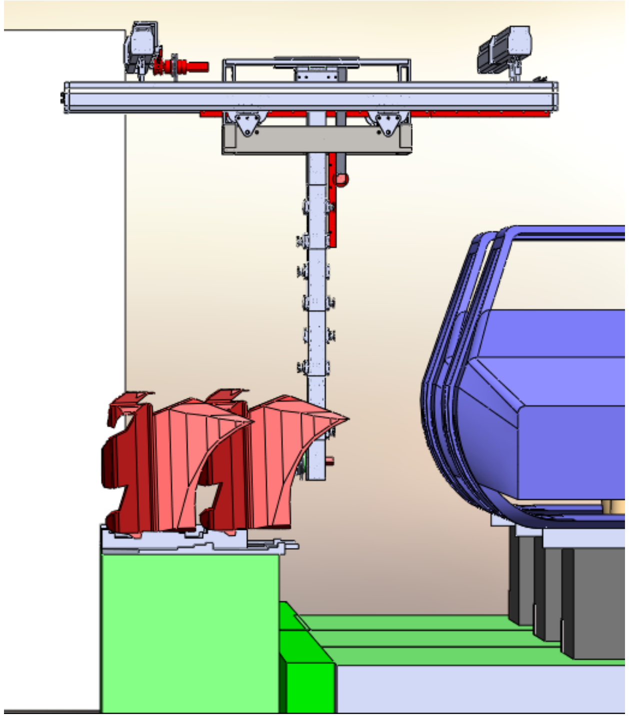

B-PaDY

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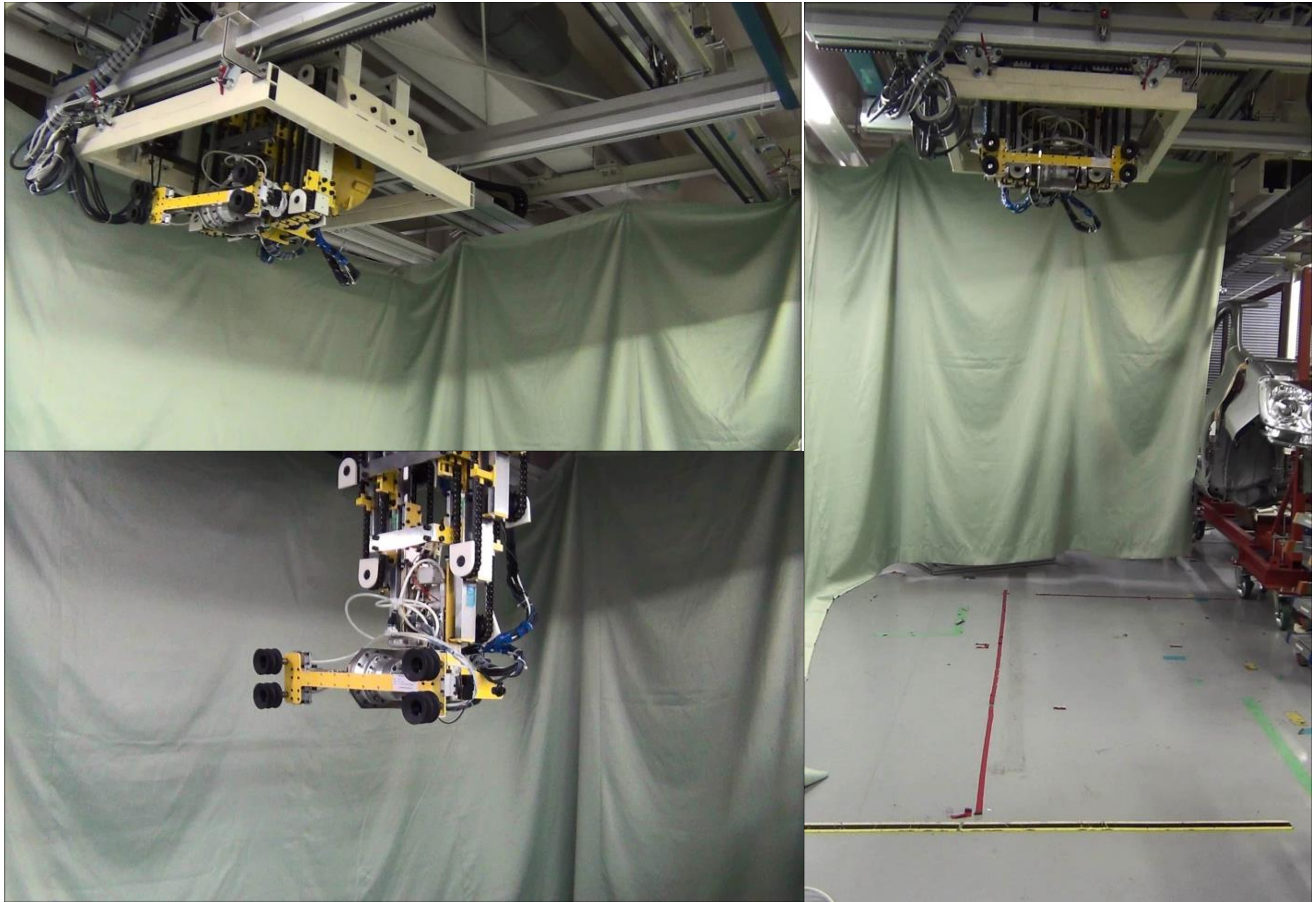

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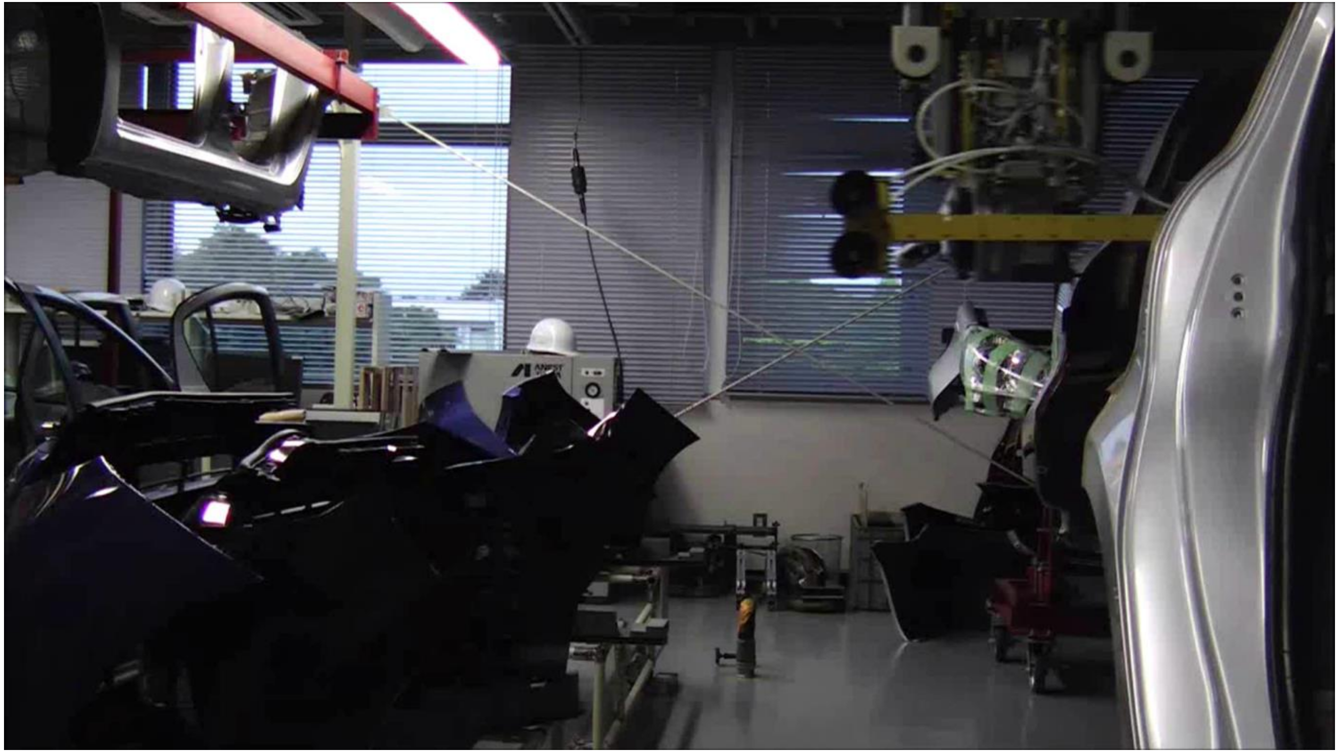
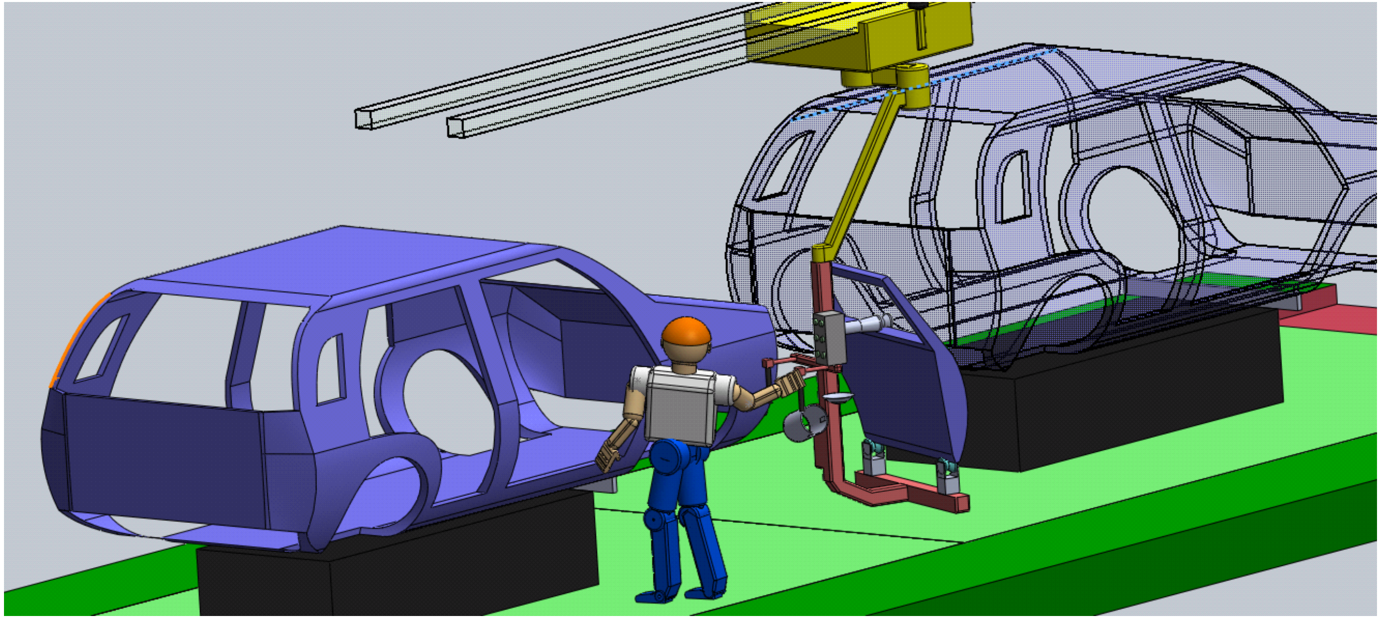
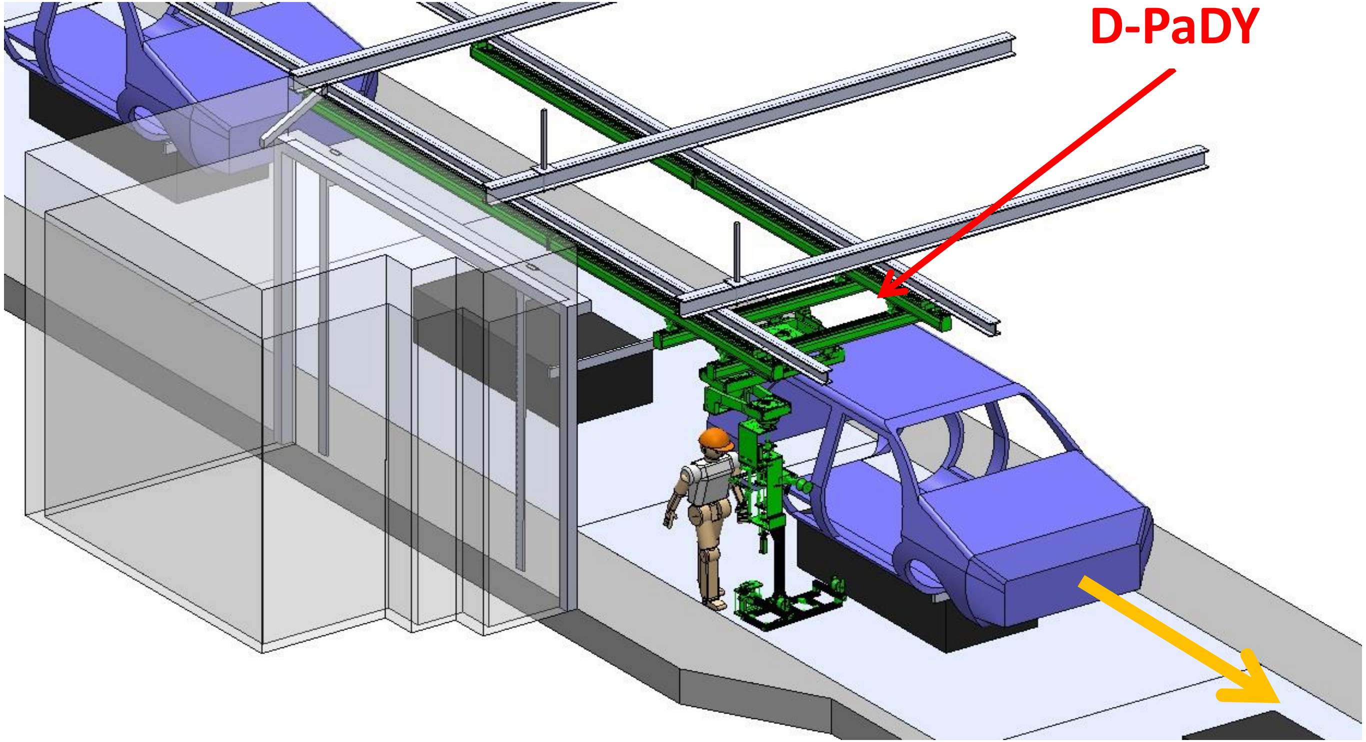


D-PaDY

D-PaDY



D-PaDY



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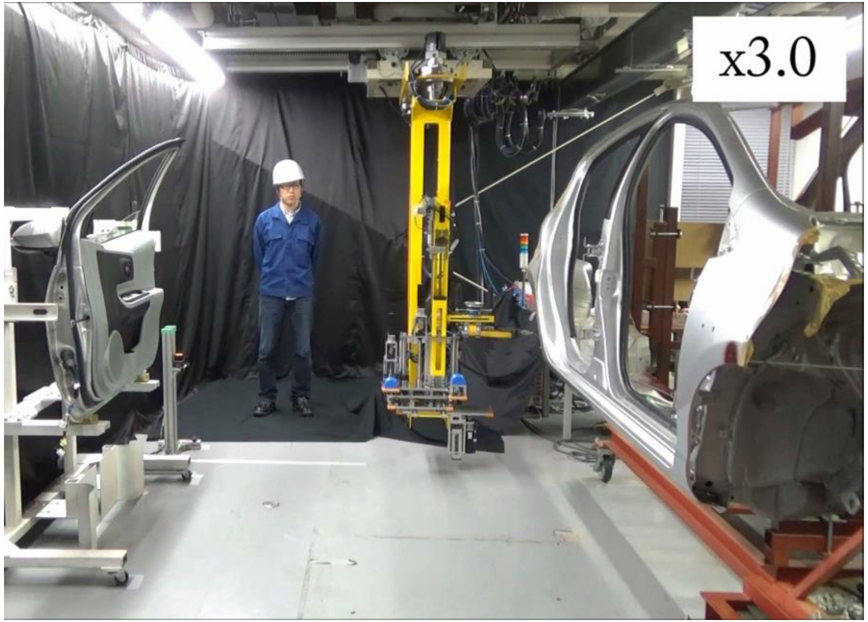
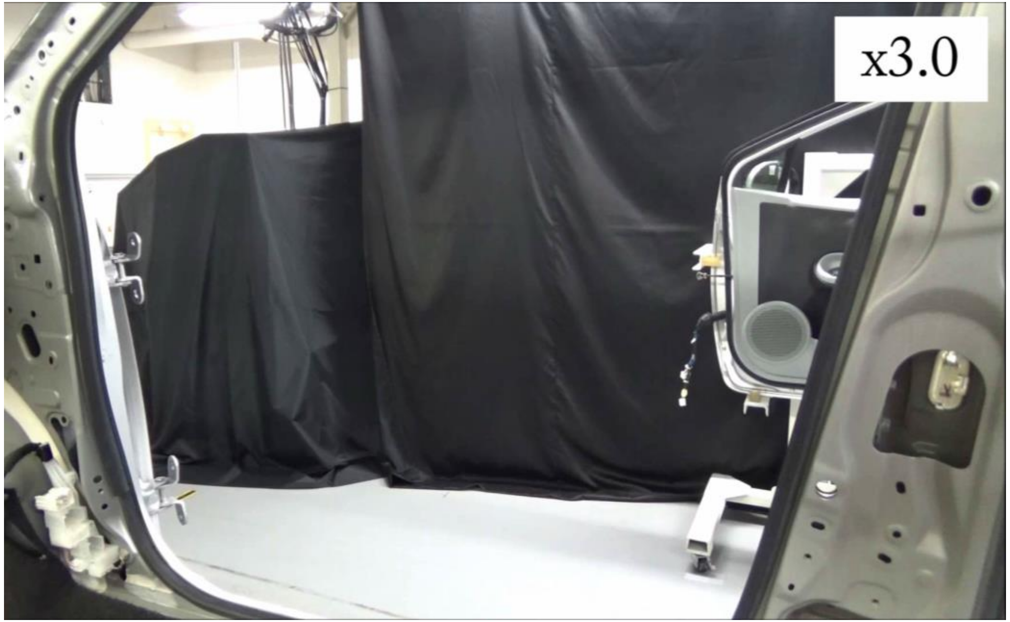
D-PaDY

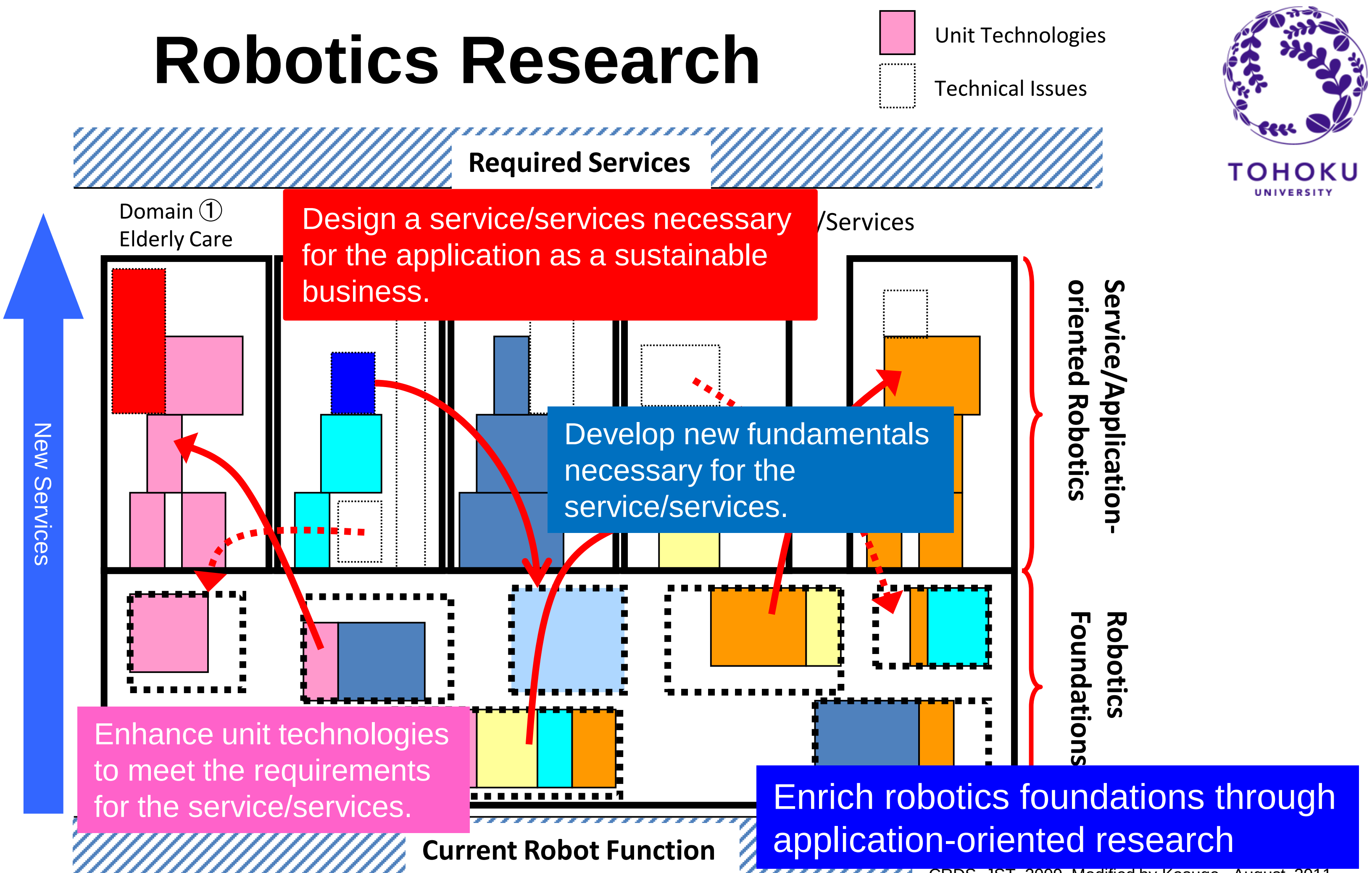




Conclusions

- Overview of Robotics has been introduced.
- Dance Partner Robots, PBDR and RoboDANTE have been introduced as research platforms for pHRI (Physical Human-Robot Interaction).
- The platforms have given us opportunities to reconsider issues relating to pHRI.
- PaDY has been introduced as examples of applications of pHRI.
- HRI will open new applications in many manufacturing processes.

Robotics Research



CRDS, JST, 2009, Modified by Kosuge, August, 2011