Human-Robot Collaboration in Construction

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Outline

- Motivation
- Safety regulations
- Attention zone of human workers
- Avoidance zones
- Path planning for mobile robots operating alongside with human worker
- Unanticipated contact on a construction site
- Conclusion and future work

Motivations

- **Rise of Human-Robot Collaboration:**
  - Robots work in close proximity to humans.
  - Opportunities for increased productivity.
  - Challenges in ensuring smooth, safe interactions.
- **Safety Remains a Concern:**
  - Ensuring robots function safely in environments where they interact with humans.
  - Especially during unpredictable or unintended events.
  - Remains a top priority in the design and control of these systems.

Regulation of Safety Standards

- **Presence-sensing robotic devices**
  - R15.06-1: The speed of a collaborative robot's end-effector is regulated to ensure safe interaction by setting limits based on proximity to human operators.
  - R15.08-1: Determining the stopping distance of a mobile robot, which is contingent upon factors such as its maximum-rated load, velocity, and the operating environment.
  - R15.08-2: Regulates the permissible moving speeds of the mobile robot, stipulating that it should operate at 33%, 66%, and 100% of its rated speed with corresponding rated load percentages.

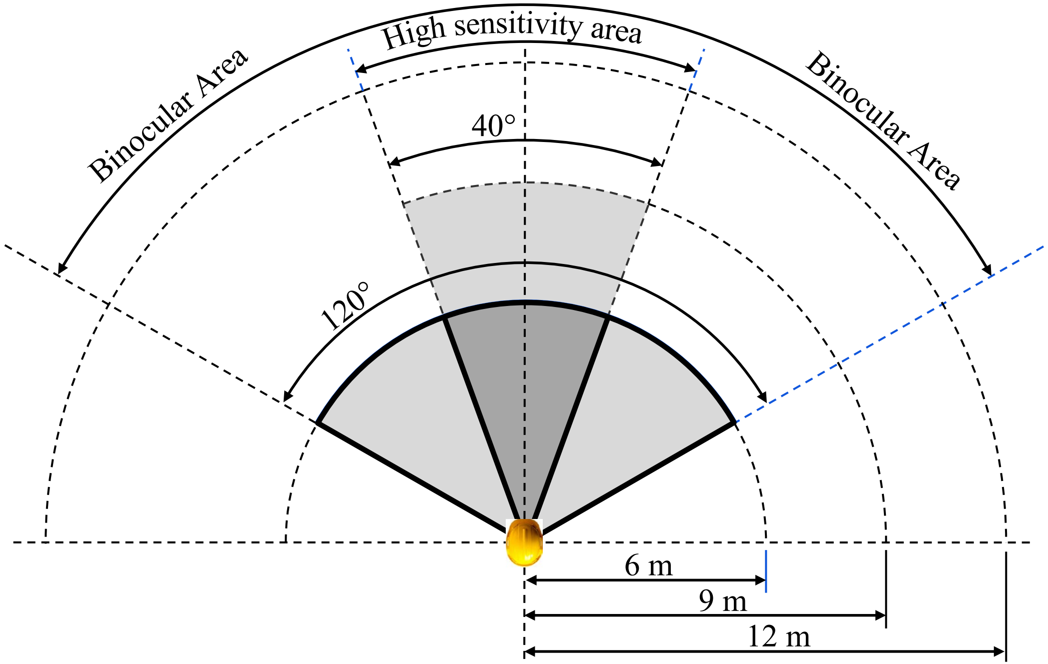
Motivations

- **Risk of Unexpected Contacts:**
  - Presence of robots in human-centric environments.
  - Increased risk of accidental or unexpected physical contact
  - Need for more advanced control systems and better predictive capabilities to prevent harmful incidents.
- **Research Aim:**
  - To address these challenges by developing new path planning methods that can allow robots to work more effectively and safely with humans in dynamic, real-world environments.
  - To determine the adequate moving speeds of robots for unanticipated contact on a construction site.

Identification of Attention Zone and Contact Avoidance Zones in Human-Robot Collaborative Workspaces

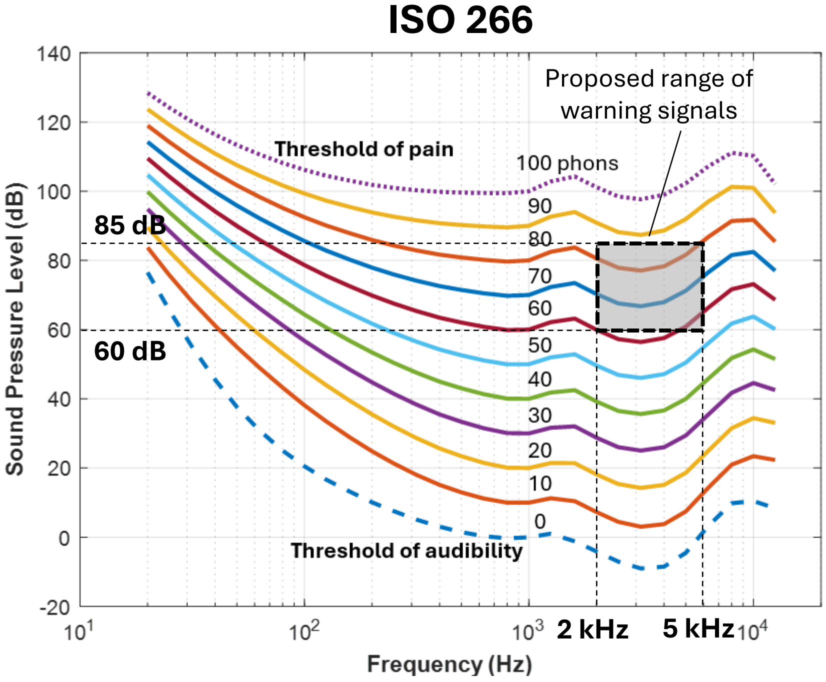
Attention Zone of Human Vision

- **Field of view**
  - Forward-facing horizontal arc: ~210°
  - Binocular field: ~120°
  - Total vertical range of the human visual field: ~150°
  - High sensitivity area: ~40°
  - 6/6 vision: 6 m



Attention Zone of Audible Region

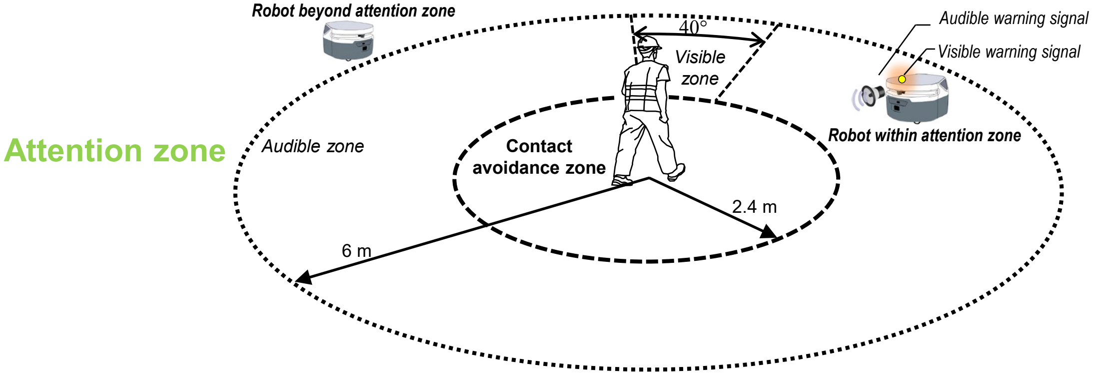
- NIOSH recommends limiting a worker's equivalent noise exposure to 85 dBA over an 8-hour day[1].
- Human auditory system is most receptive to frequencies between 2 kHz and 5 kHz.
- With a point source emitting 0.05 W of acoustic power, the sound pressure can reach 80.43 dBA at a distance of 6 m



1. NIOSH. (1992). NIOSH recommendations for occupational safety and health. Compendium of policy documents and statements.

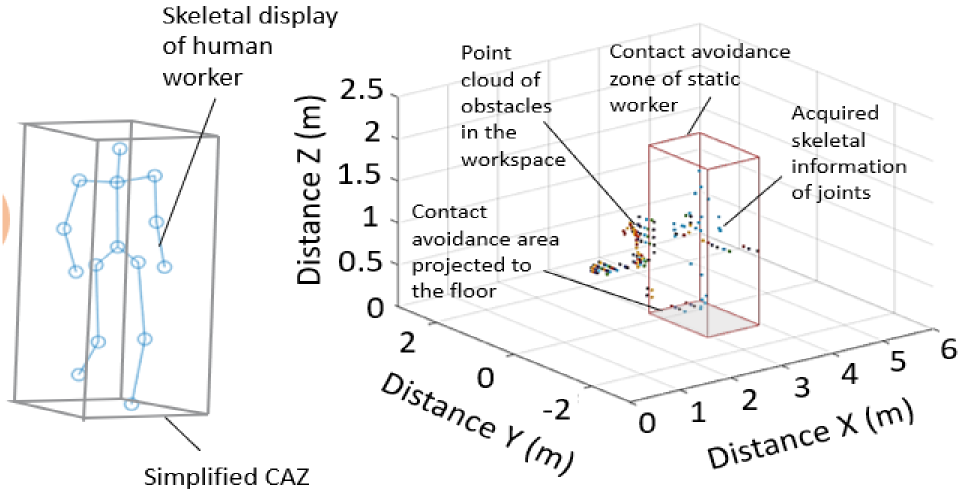
Proposed Attention Zone

- The visible zone extends in a fan shape, spanning 40° in front of the worker and extending to a radius of 6 m.
- The audible zone covers a circular area with the same radius of 6 m with a 0.05 watts point sound source.
- The average speed of a human worker: ~1.6 m/s (ISO/TS 15066).
- Map refresh rate: 1.5 seconds.



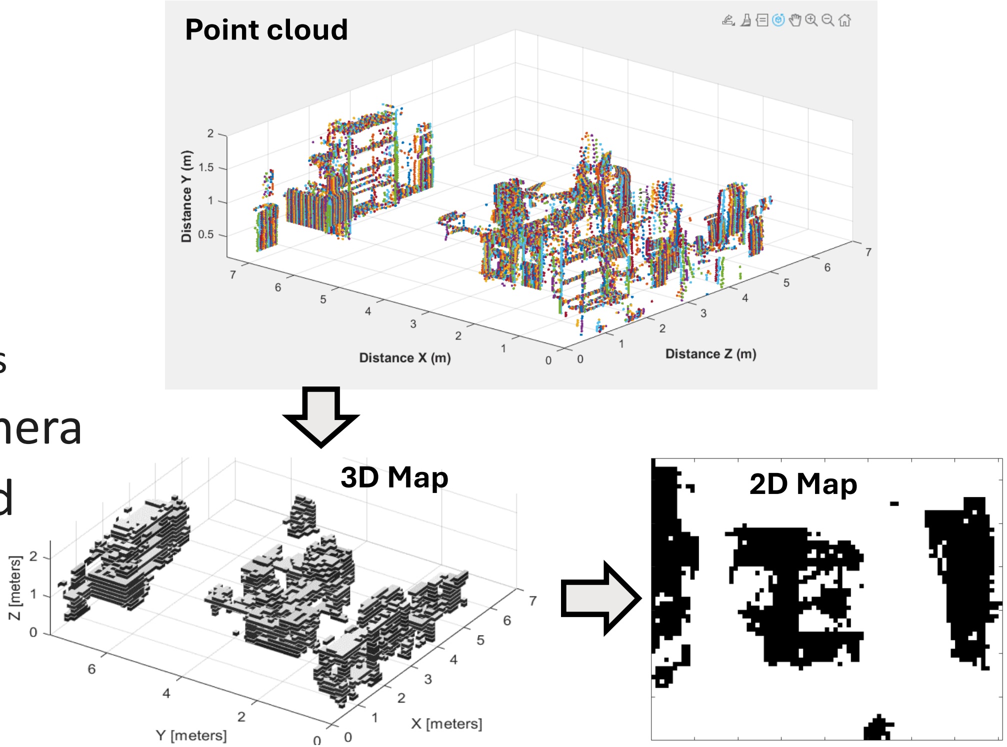
Contact Avoidance Zone for Static Workers

- Configuration space of individual joint
- Simplified contact avoidance zones



Experimental Environment

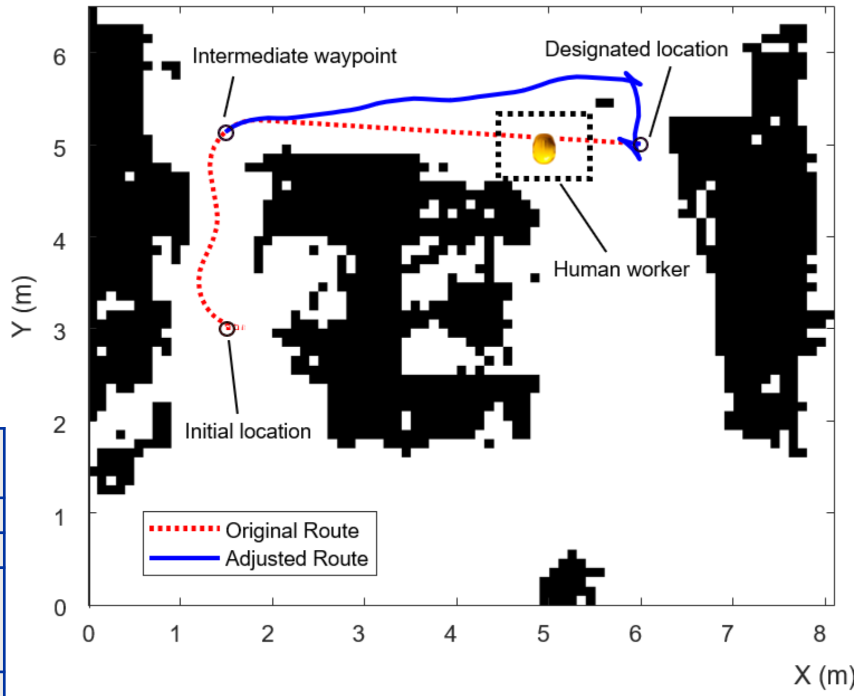
- Map of workspace
  - Locations and sizes of fixed structures
  - Location of robot itself
  - Moving trajectories of human workers
- Indoor mapping using depth camera
- Converted map using point cloud
- Map update on-the-fly



Path Planning with Static Worker

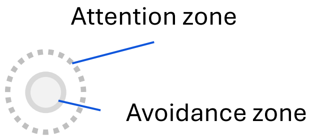
- **Three methods were evaluated:**
  - A* algorithm
  - Rapidly-exploring random tree (RRT) algorithm
  - Probabilistic roadmap (PRM) path planning algorithm

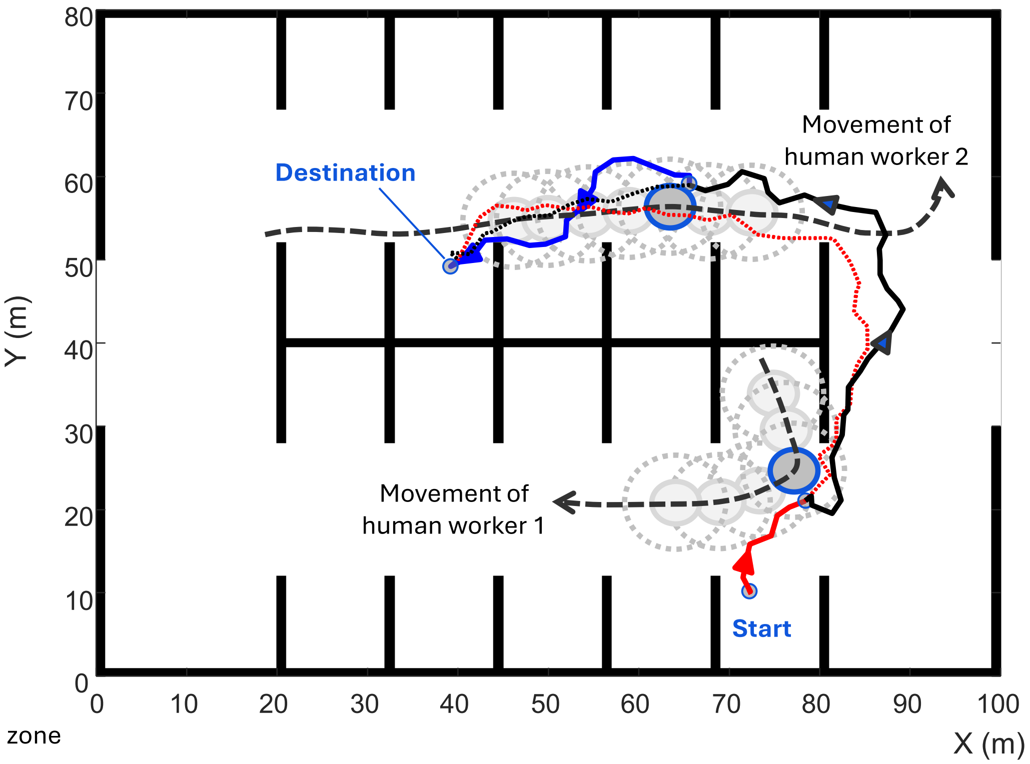
Path Planning Method	A*	RRT	PRM
Original map	73 waypoints	3000 nodes	20 waypoints
Process time	0.059 sec	1.24 sec	0.27 sec
Updated map	71 more waypoints	*3000 more nodes*	15 more waypoints
Updated time	0.559 sec	0.369 sec	0.27 sec



Path Planning with Moving Worker

- Probabilistic Roadmap (PRM) path planning method was adopted.
- An emulated warehouse setting, covering an 80 m × 100 m area
- The control unit of the mobile robot generated and updated paths within an average time of 0.87 sec, with the longest calculation time recorded at 1.20 sec.

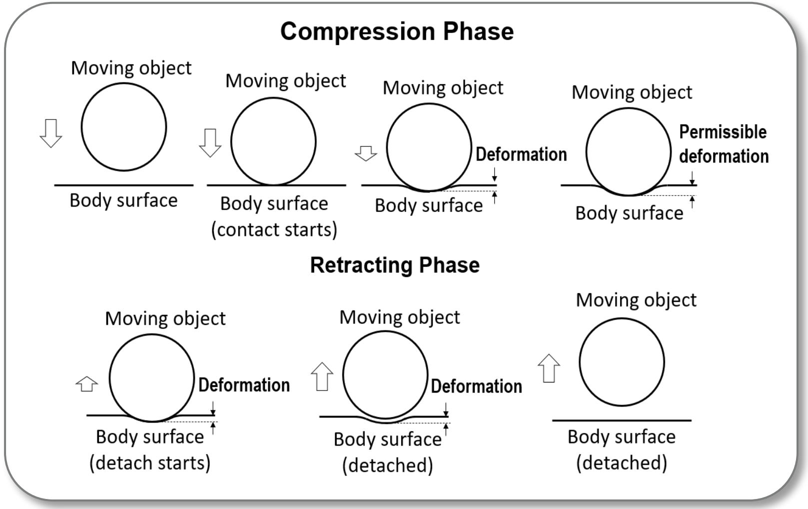


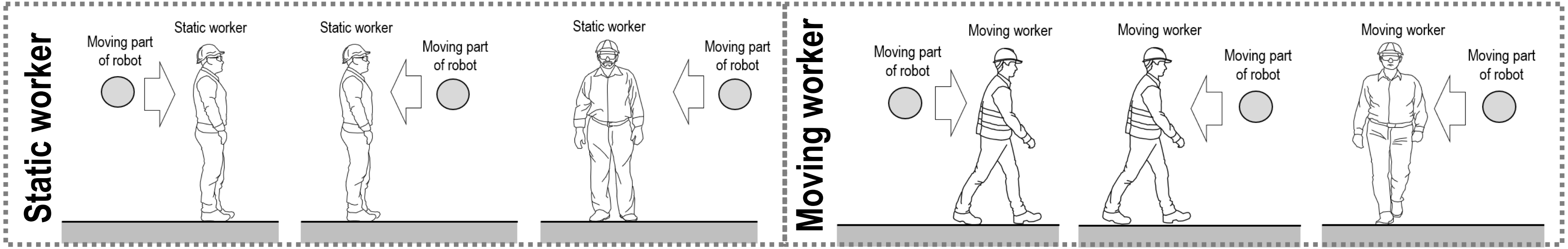


Unanticipated Contact on a Construction Site

Goals

- Understand the potential injuries created by unexpected collisions occurred in the collaborative workspaces
- Investigate the safety operation of robotic devices and minimize the injury caused by unexpected human-robot impact





Dynamic Model of Impact Scenarios

- **Each model of the impact scenarios are divided into two phases.**
  - First phase (compression phase): starting from the contact between the object and the human body surface, until the compression reaches the permissible deformation of the human body.
  - Second phase (retraction phase): the body surface begins to recover from its permissible deformation to its original state.

Struck and Pushed

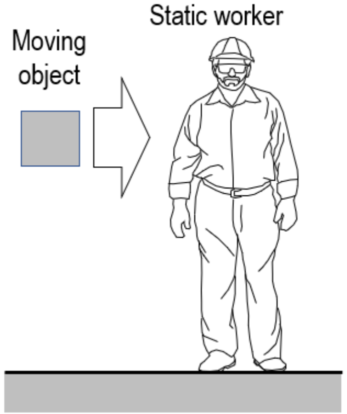
- **Dynamic model human-robot impact**

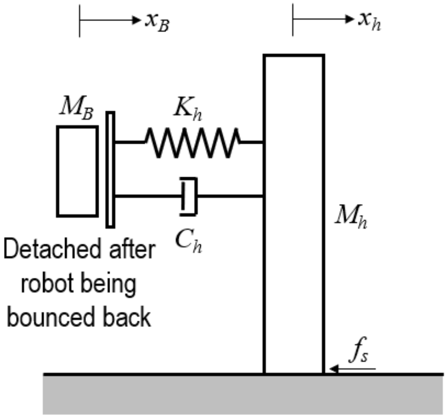
$$M_B\ddot{x}_B + C_h\dot{x}_B - C_h\dot{x}_h + K_h x_B - K_h x_h = 0$$

$$M_h\ddot{x}_h + C_h\dot{x}_h - C_h\dot{x}_B + K_h x_h - K_h x_B + f_s = 0$$

$$\Delta s = x_B - x_h.$$

horizontal movement of object: x_B
horizontal movement of worker's body: x_h
mass of the moving object: M_B
mass of the human body: M_h
stiffness of the contact surface of the body part :K_h
corresponding viscous damping: C_h
static friction between the shoes and the ground: f_s
compression of the body at the impact location: Δs





Struck and Bent

- **Dynamic model human-robot impact**

$$M_B\ddot{x}_B + C_h\dot{x}_B - \frac{C_h l_u}{2}\dot{\theta}_u + K_h x_B - \frac{k_\theta l_u}{2}\theta_u = 0$$

$$\frac{M_{hu} l_u^2}{4}\ddot{\theta}_u - \frac{C_h l_u}{2}\dot{x}_B + \left(C_\theta + \frac{C_h l_u^2}{4}\right)\dot{\theta}_u - \frac{k_\theta l_u}{2}x_B + \left(\frac{K_h l_u^2}{4} + k_\theta\right)\theta_u = 0$$

$$\Delta s = x_B - x_h = x_B - \frac{l_u}{2}\theta_u.$$

horizontal movement of object: x_B
horizontal movement of worker's body: x_h
mass of the moving object: M_B
mass of the human body: M_h
stiffness of the contact surface of the body part :K_h
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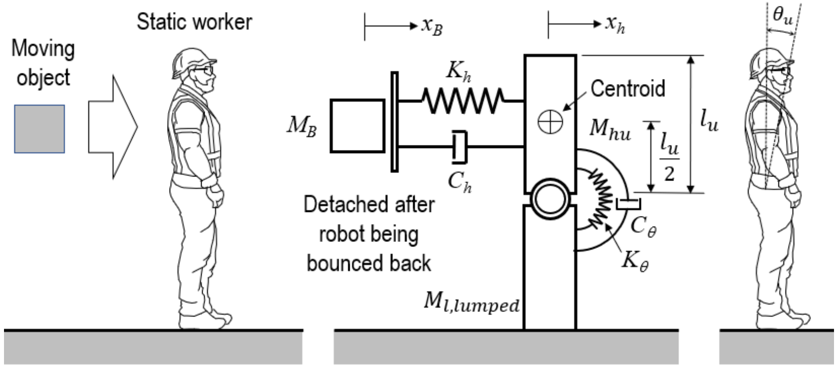


Allowed Pressure and Permissible Deformation

- **Allowed pressure and permissible deformation listed in ISO/TS 15066**

Body part	Impact force (N)	Surface Pressure (N/mm^2)	Stiffness (N/mm)
Skull/forehead	175	0.3	150
Face	90	0.2	75
Neck (sides/neck)	190	0.5	50
Neck (front/larynx)	35	0.1	--
Back/shoulders	250	0.7	35
Chest	210	0.45	25
Belly	160	0.35	10
Pelvis	250	0.75	25
Buttocks	250	0.8	--
Upper arm/elbow joint	190	0.5	30
Lower arm/hand joint	220	0.5	40
Hand/finger	180	0.6	75
Thigh/knee	250	0.8	50
Lower leg	170	0.45	60
Feet/toes/joint	160	0.45	--

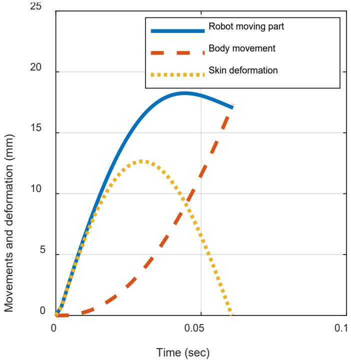
Physical Parameters of Human Body

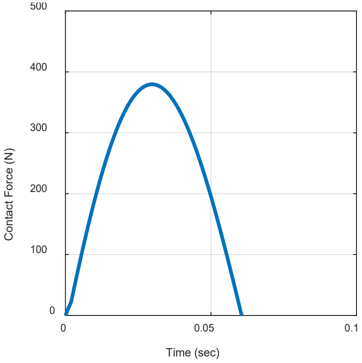
- **Estimation of upper limit of the moving speed of construction materials carried by the robot**
  - Object 1: 203.2 mm × 203.2 mm × 406.4 mm (~17 kg)
  - Object 2: 203.2 mm × 304.8 mm × 406.4 mm (~25 kg)
  - Worker's height and the weight: 1.75 m and 90.71 kg,
- **ISO/TS 15066: The constant force applied to the back of the human body should not be greater than 250 N.**
- $Permissible\ deformation = 2 \times \frac{Allowable\ force}{Stiffness}.$

*Object used: concrete mansion units used on construction sites

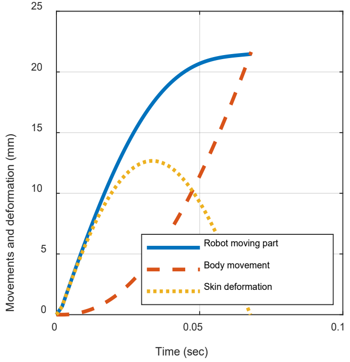
Simulated Results – Struck and Pushed

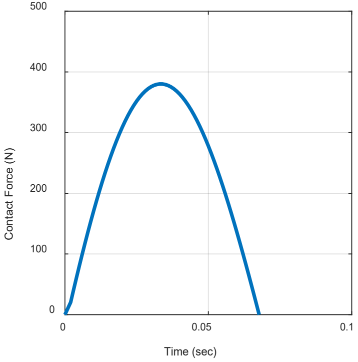
Object 1: 17 kg (760 mm/s)





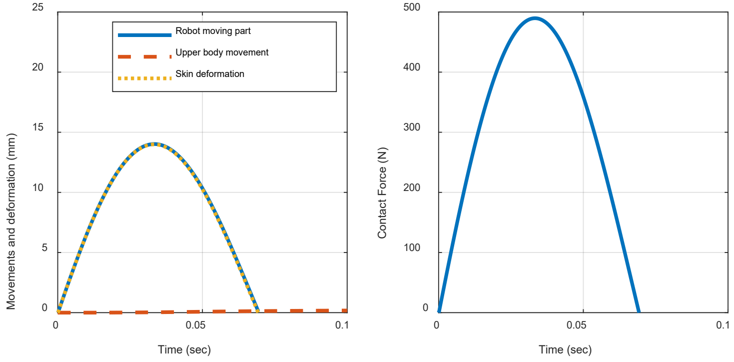
Object 2: 25 kg (680 mm/s)



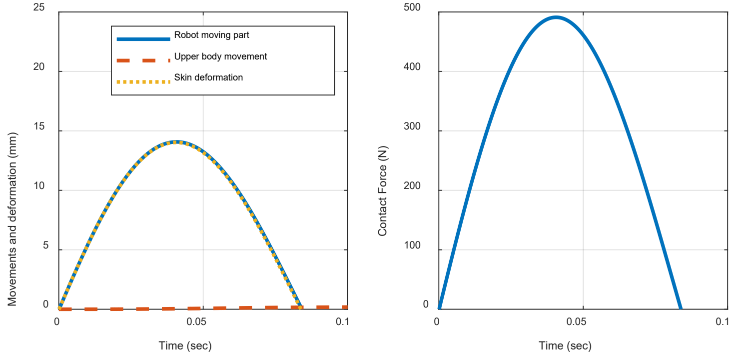


Simulated Results – Struck and Bent

Object 1: 17 kg (760 mm/s)



Object 2: 25 kg (570 mm/s)



Simulated Results – Minimizing Permissible Deformation on Body Surface

	Struct and Bent (Back)				Struck and Pushed (Upper Arm)			
M_B	17 kg		25 kg		17 kg		25 kg	
$\dot{x}_B$ (mm/s)	Δs (mm)	F_c (N)	Δs (mm)	F_c (N)	Δs (mm)	F_c (N)	Δs (mm)	F_c (N)
200	4	140	4.9	172	2.2	65	2.3	70
300	6	210	7.4	258	3.9	117	4.3	128
400	8	280	9.8	345	5.7	172	6.4	192
500	10	350	12.3	431	7.6	229	8.6	258
600	12	420	14.8	517	9.5	286	10.9	326
700	14	490	17.2	603	11.5	344	13.1	394
800	16	560	19.7	689	13.4	403	15.4	463
900	18	630	22.1	775	15.4	462	17.7	532
1000	20.0	700	24.6	861	17.4	521	20.1	602

- As the contact velocity increases, the chance of deformation and potential injuries both increases.
- To maintain the permissible deformation of body surface
  - 17 kg block: < 760 mm/s
  - 25 kg block: < 570 mm/s

Conclusions and Looking Ahead

- Addressed the challenge of preventing collisions between mobile robots and human workers in collaborative workspaces.
- Methodology for delineating attention zones for human workers and avoidance zones for robots.
- **Estimation of adequate moving speeds of carried objects in the workspaces.**

Questions?

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