Solutions for the construction site of the future

The autonomous excavator project T.H.O.R.

Robotics Research Lab
Department of Computer Science
University of Kaiserslautern

15th June 2012

The robotics research lab

- Department of computer science at the University of Kaiserslautern
- Head: Professor Dr. Karsten Berns
- 20 PhD students
- Indoor and outdoor robot projects

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T.H.O.R. (Terraforming Heavy Outdoor Robot)

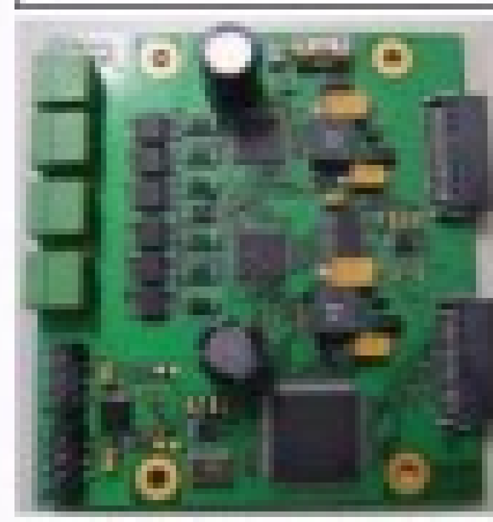
Volvo EW/180B

M	2.92 m
L	8.72 m
C	3.17 m
E	1.29 m

- Mass: 18t
- Lifting force ≈ 100kN

Excavator extensions

1. Electronic control valves
2. Laser scanners
3. Boom joint sensors (elongation)
4. DSP controller boards
5. Personal Computer



Operator schedule

Time consumption:

- 5% Repositioning / special tasks
- 10% Surface shaping ⇒ precise, high variety
- 85% Mass excavation ⇒ coarse, monotonous

⇒ Automation of monotonous work parts

Additional problems

- Safe positioning
- Unclear soil conditions
- Labor time clauses
- Hazardous environments

⇒ Protect operator from dangerous situtations

Long-term project objective

"Develop a fully autonomous mobile excavator"

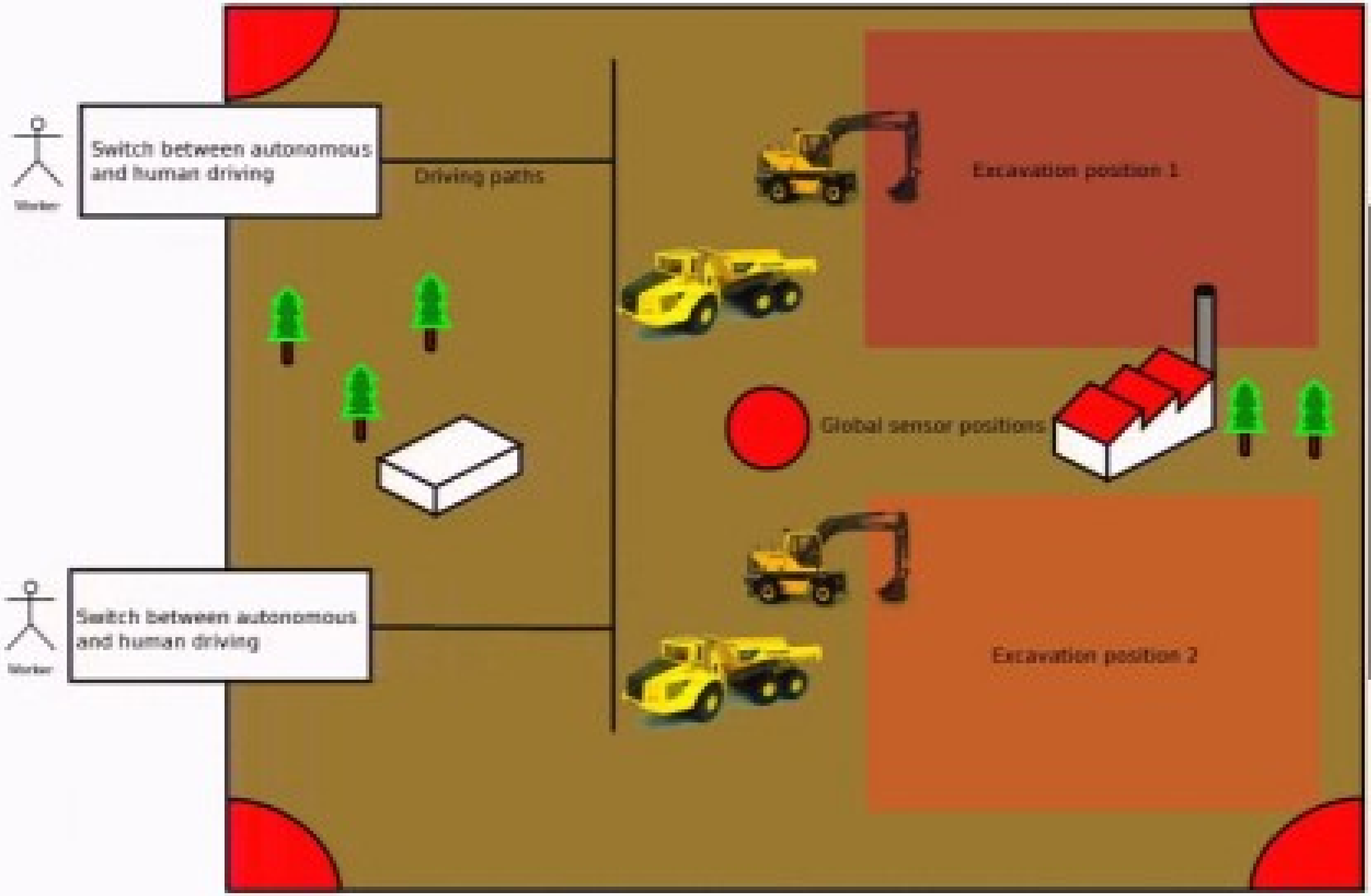
Typical operations

- Move material from a to b
- Reshape the surface (+/-)
- Continuously load trucks
- Locate & reposition on site

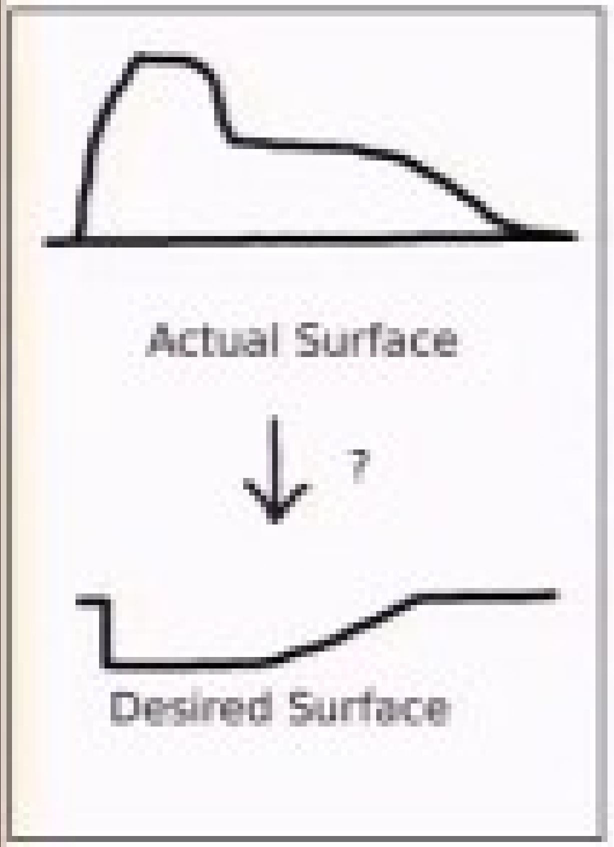
Spin-off results for the human operator

Assistance systems improving efficiency and safety

Global scenario

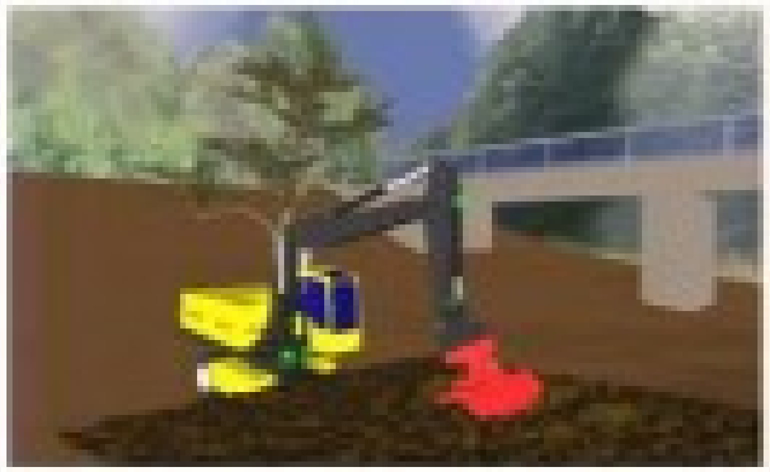


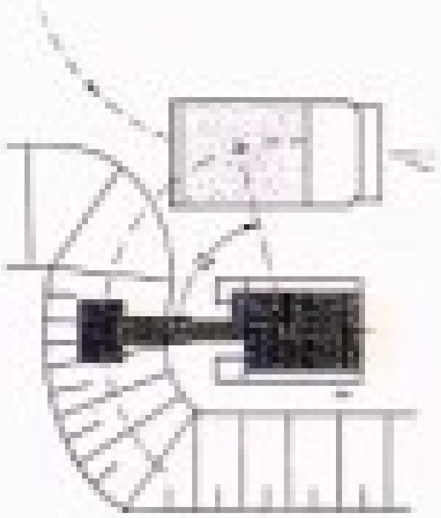
Problem:

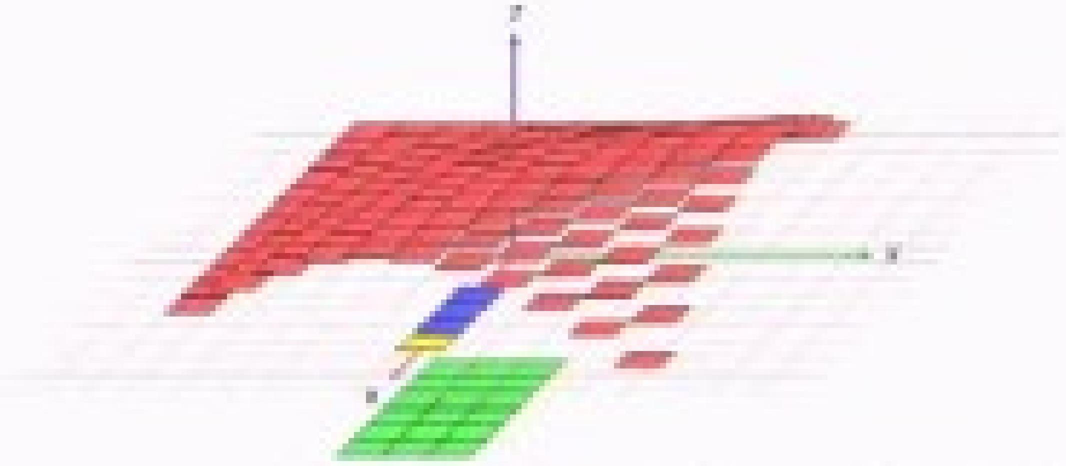


Development steps

1. Environment simulation (safe tests)
   - Simulated excavator
   - Physical objects (buildings, infrastructure . . .)
2. Perception algorithms
   - Classification of surface(s) and objects
   - Detection of changes
3. Autonomous control structure
   - Identify next excavation position
   - Perform complete shaping of the surface







System parts

Control part

- Environment perception (surface, obstacles, buildings, trucks ...)
- Local and global mapping
- Behaviour-Based control (kinematics, safe trajectories, obstacle avoidande)
- Autonomous decisions (next excavation / dumping position)

Identical interfaces

Simulation

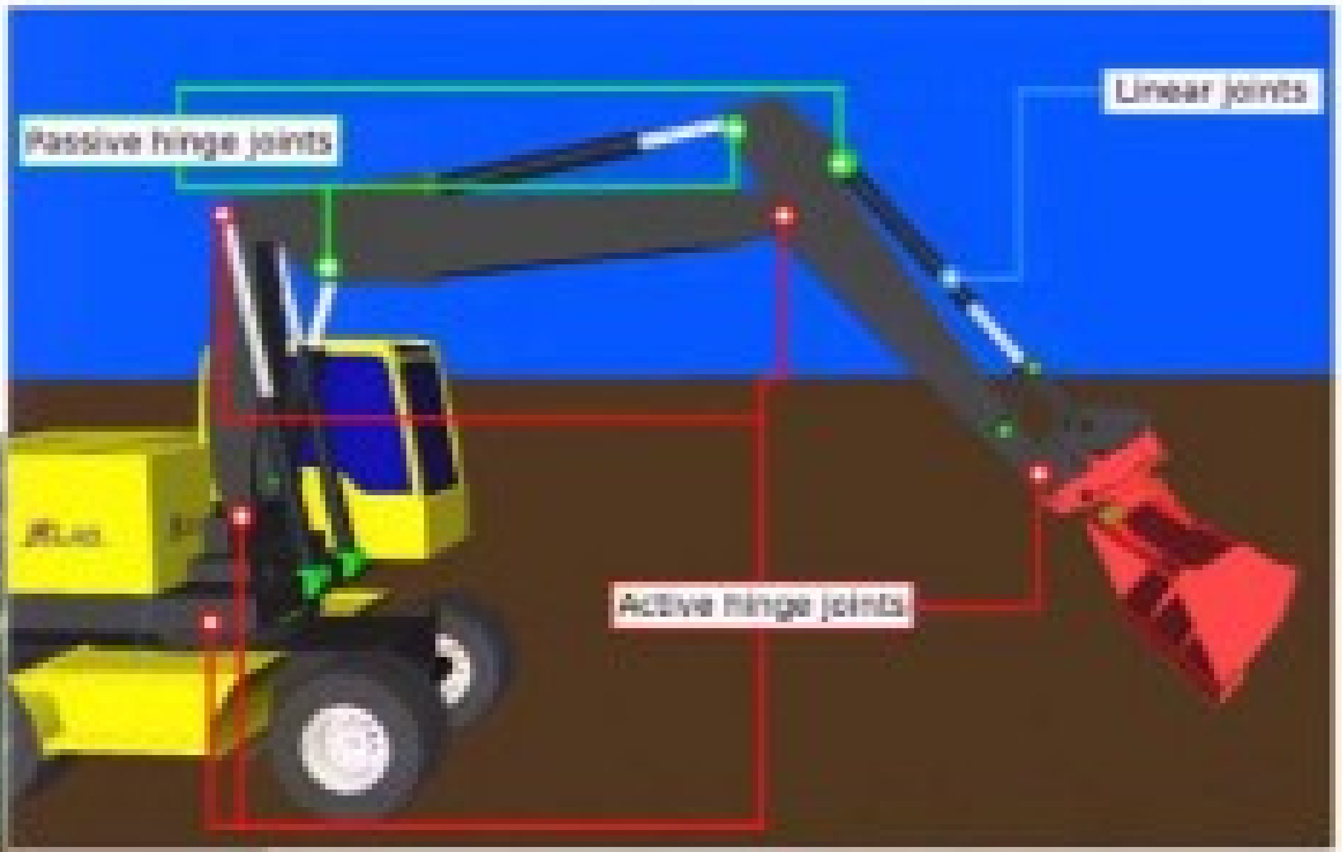
- Environment simulation (visual)
- Simulated sensor systems
- Physics simulation
- Soil simulation (GPU)

Hardware connection

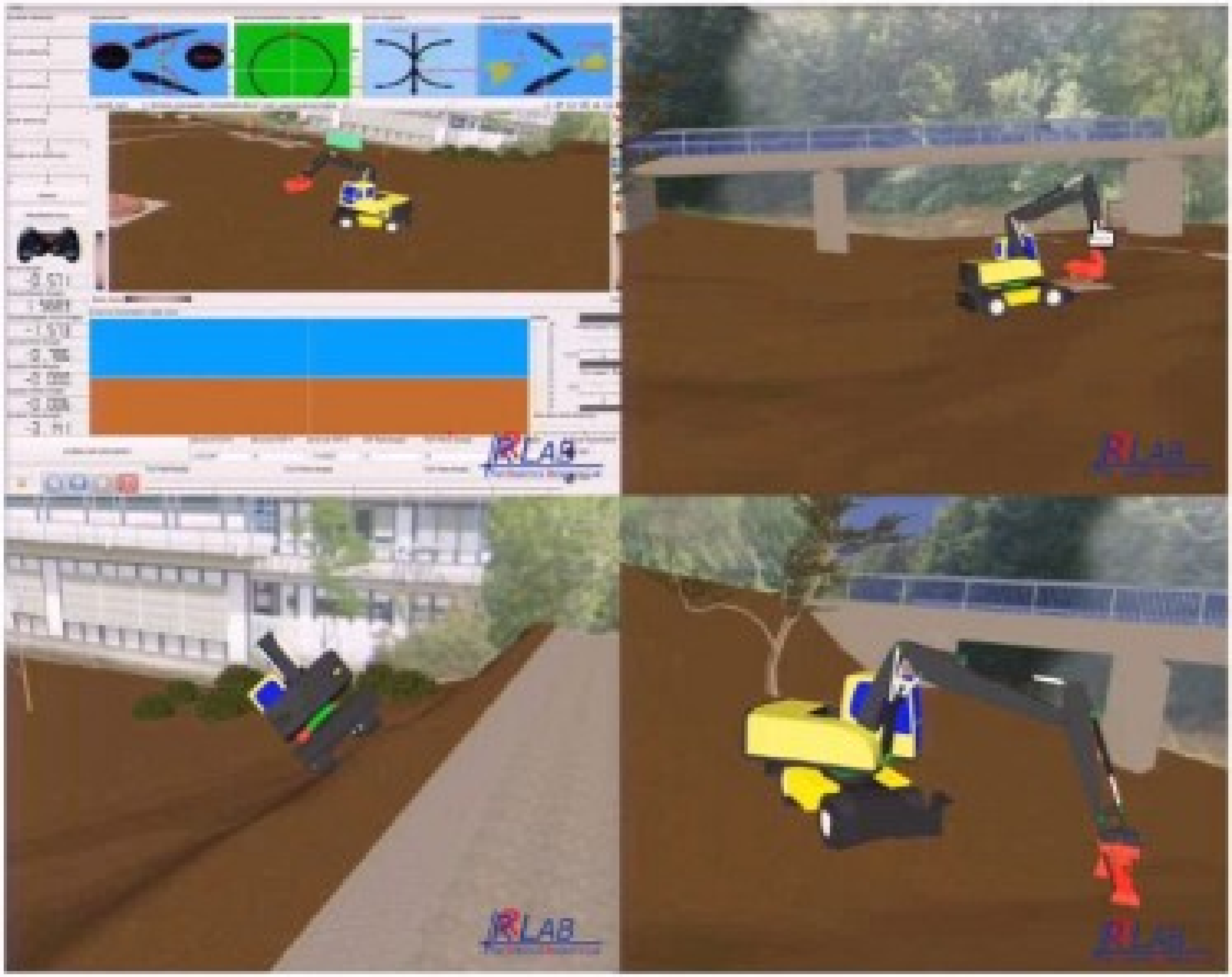
- DSP control (electrohydraulic valves)
- Pressure sensors
- Laser-scanners
- Outriggers and shield

Excavator model

- Visualization: SimVis3D
- Realism: Newton physics



Simulation videos



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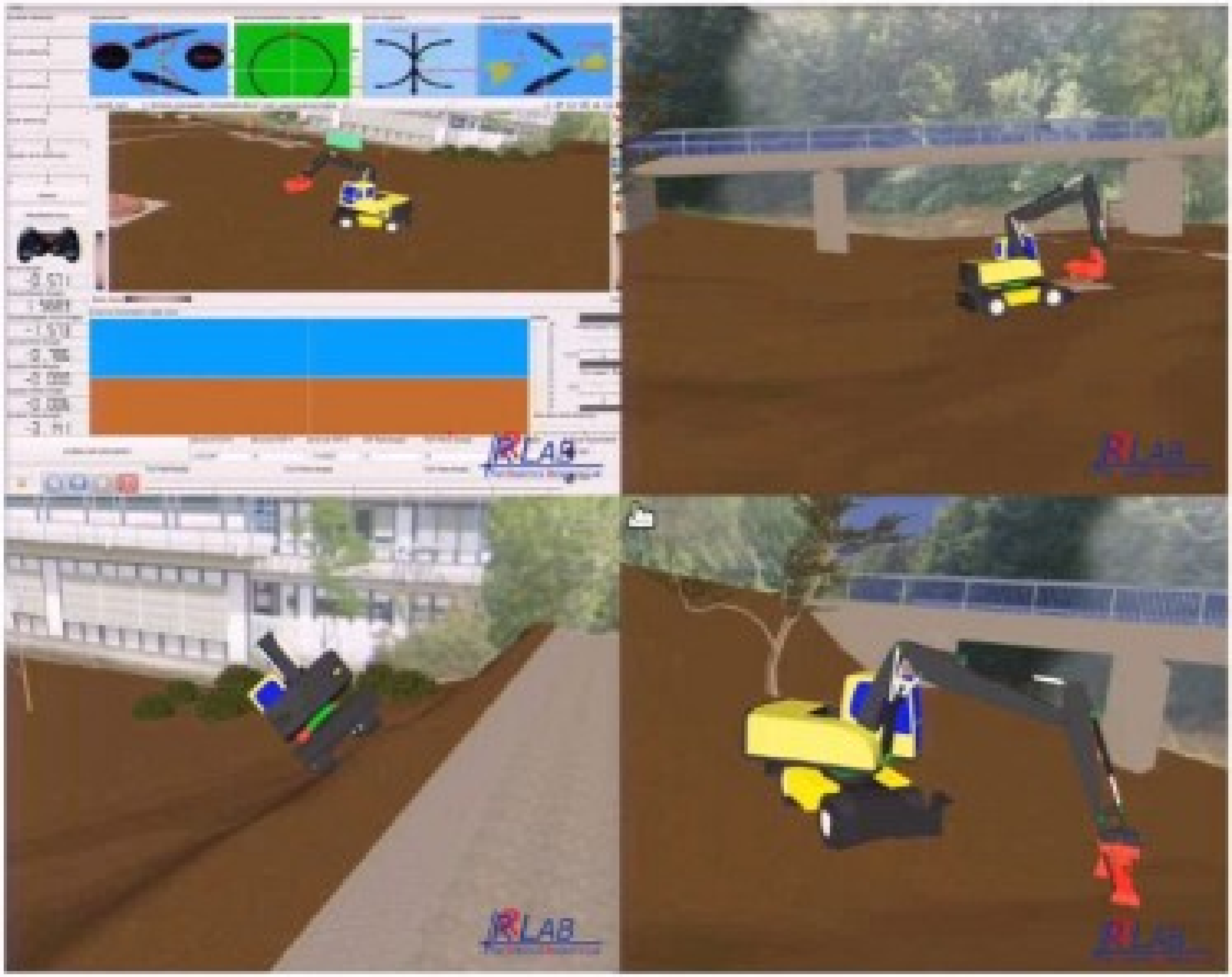

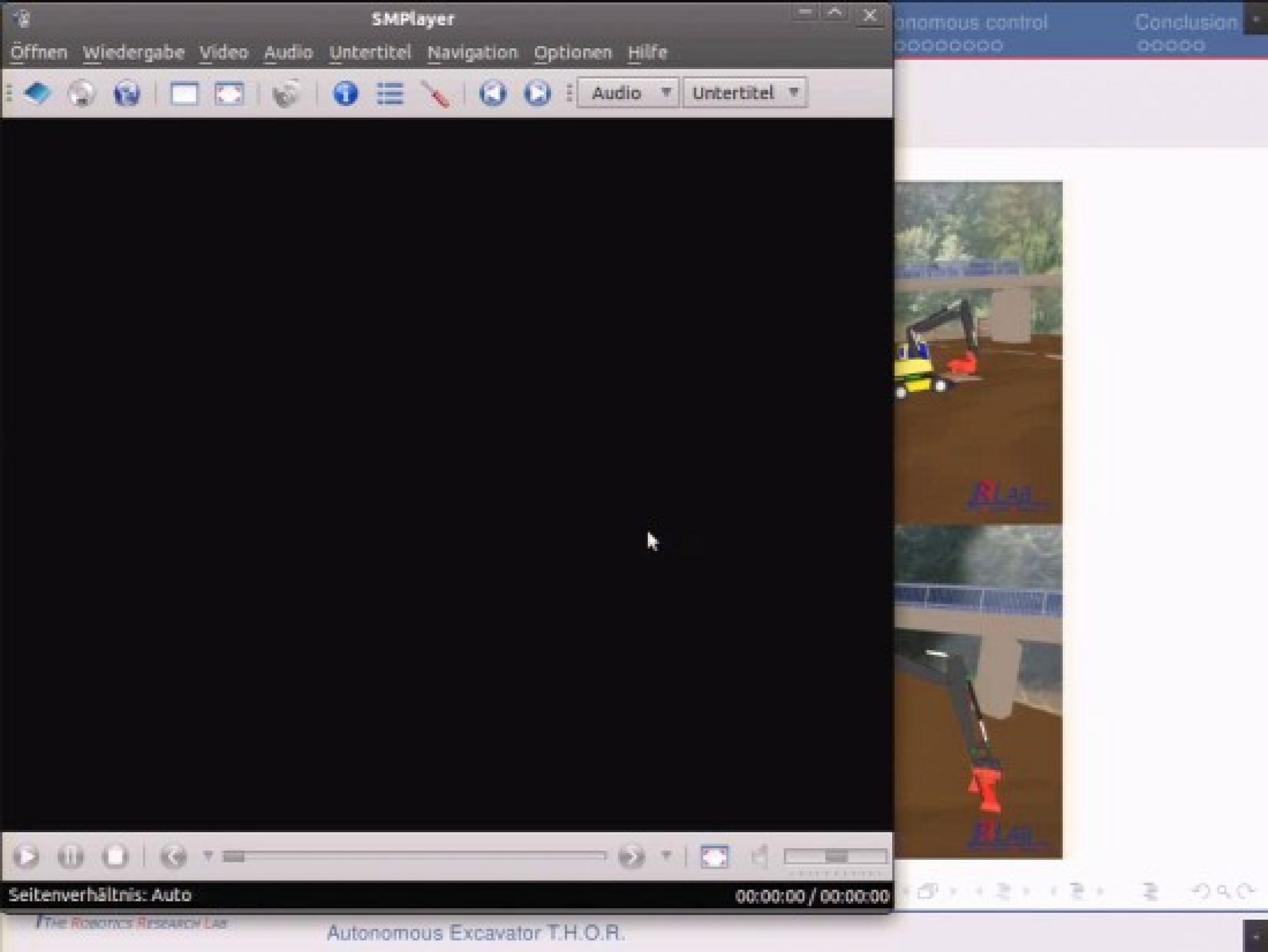
SMPlayer
Öffnen
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Video
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Optionen
Hilfe
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Untertitel
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onomous control
Conclusion
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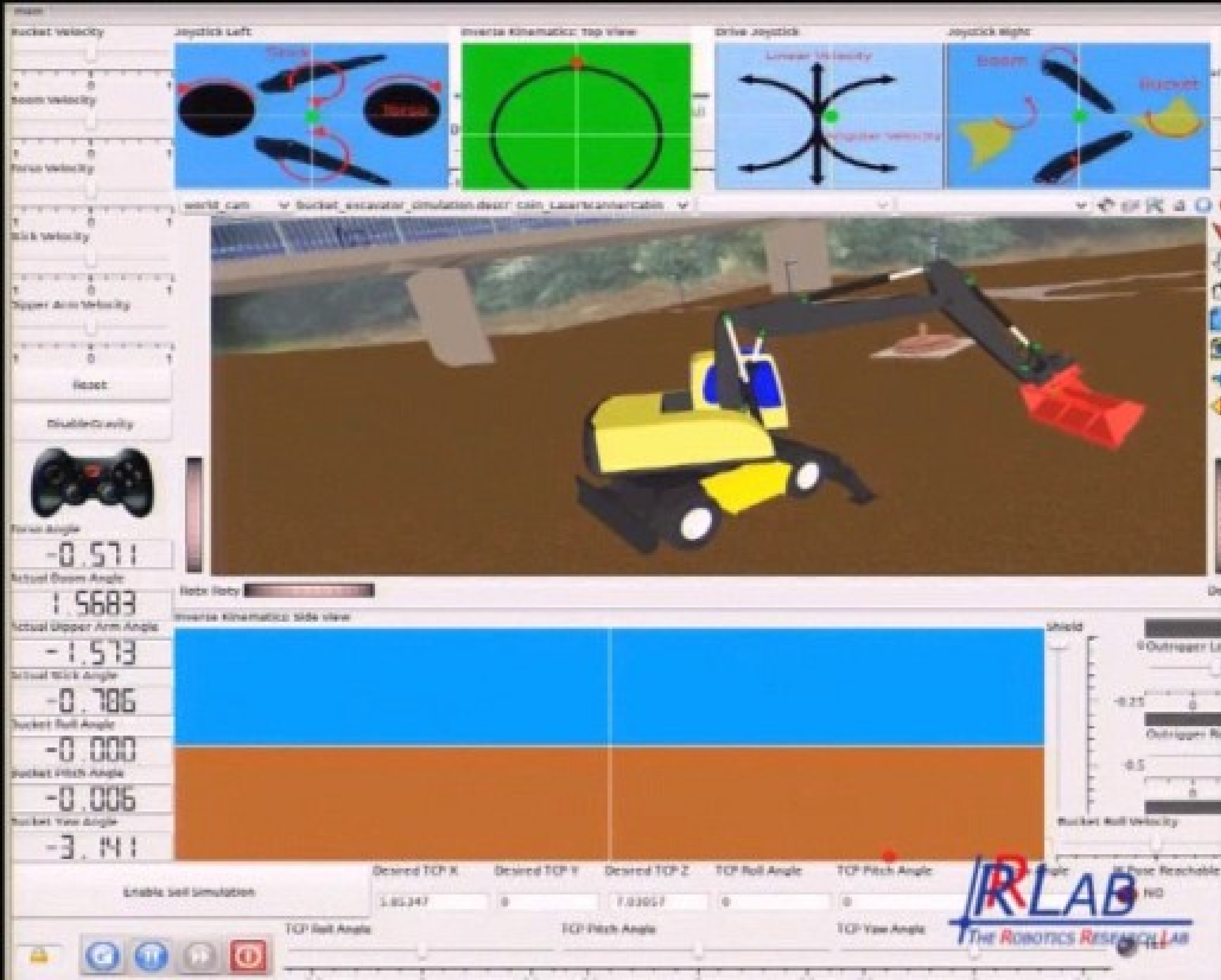
Bucket Velocity
Joystick Left
Inverse Kinematics: Top View
Drive Joystick
Joystick Right
Linear Velocity
Boom
Bucket
Reset
-0.571
1.5683
-1.573
-0.786
-0.000
-0.006
-3.141
Inverse Kinematics: Side View
Enable Soil Simulation
Desired TCP X
Desired TCP Y
Desired TCP Z
TCP Roll Angle
TCP Pitch Angle
RRLAB
THE ROBOTICS RESEARCH LAB

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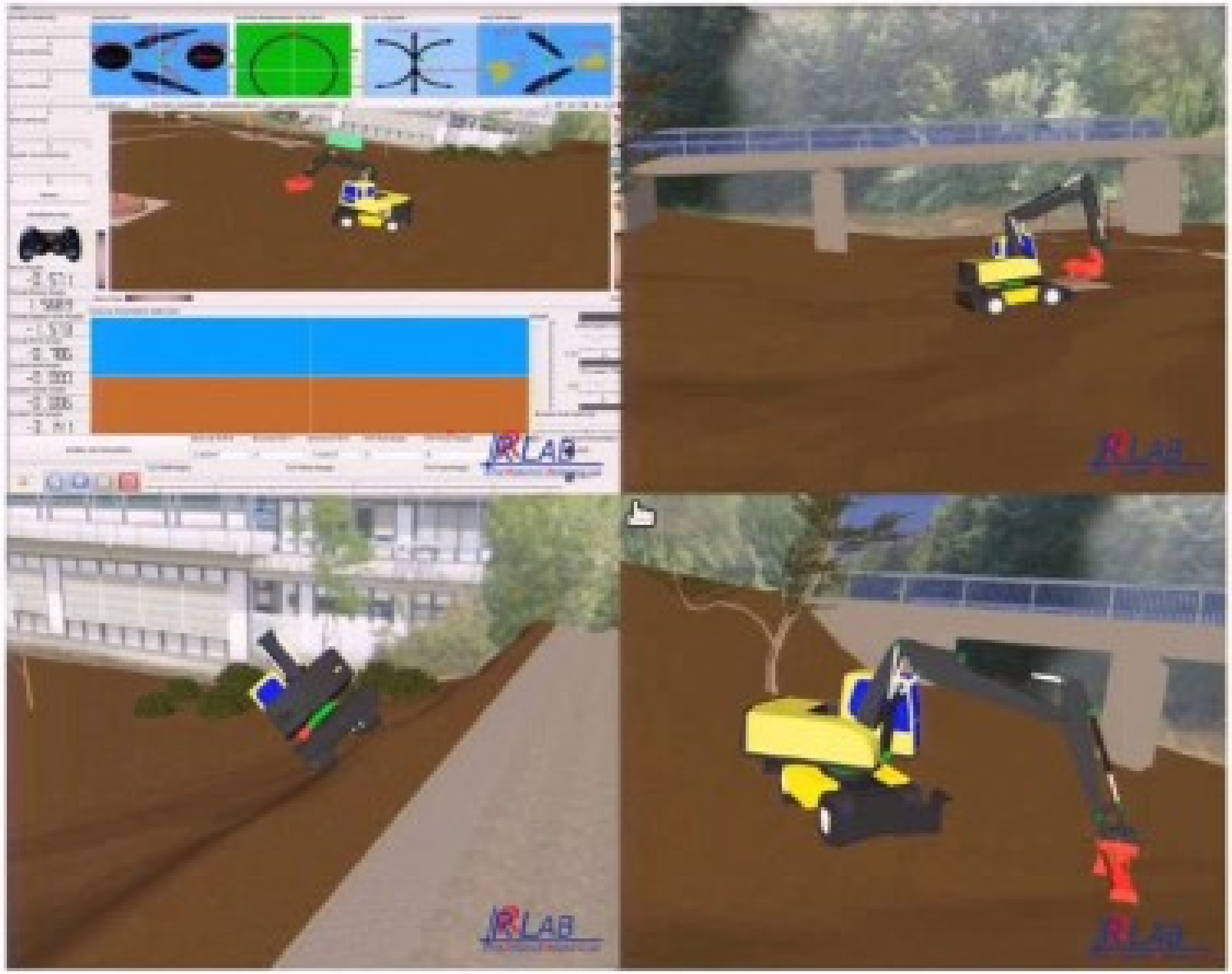
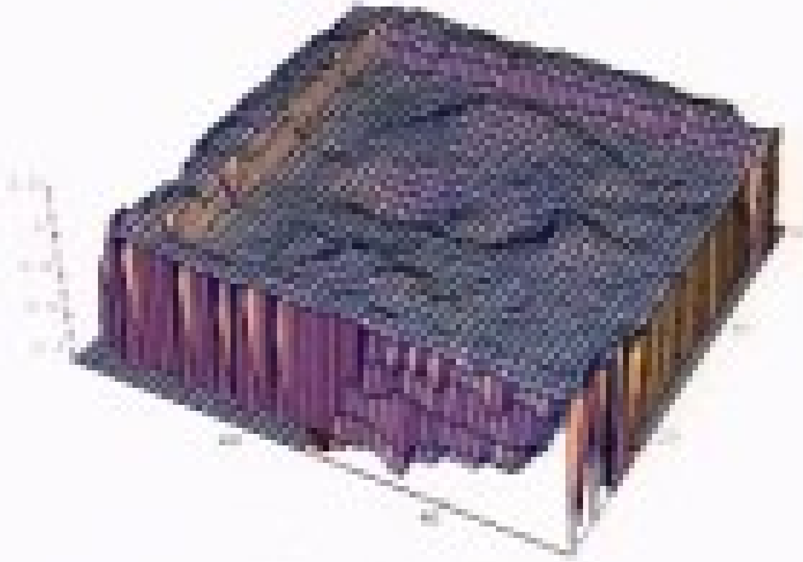


Extensions

- Existing simulation
  - Excavator physics
  - Mostly static environment
  - Noise
  - No deformable surfaces
- Additional requirements
  - Shaping the environment during the autonomous excavation process
  - Model bucket-soil interaction for perception of environment changes

⇒ Develop an efficient soil simulation

Collision model



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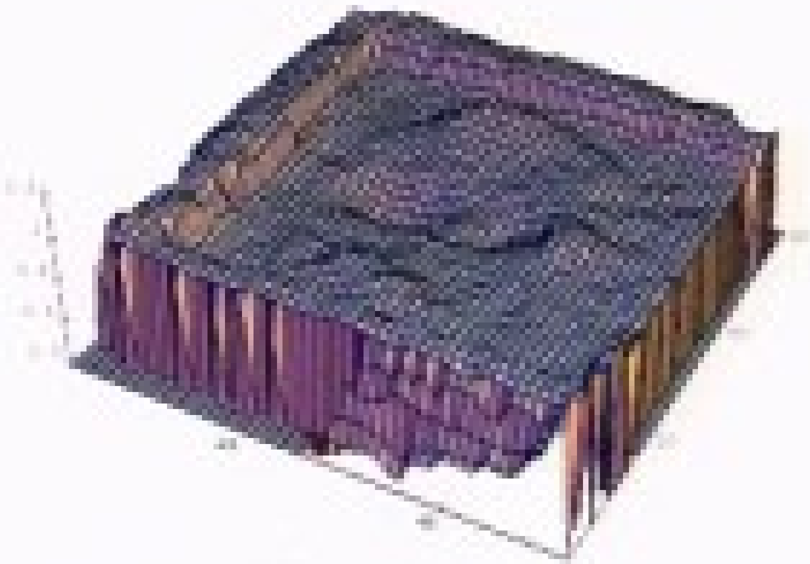

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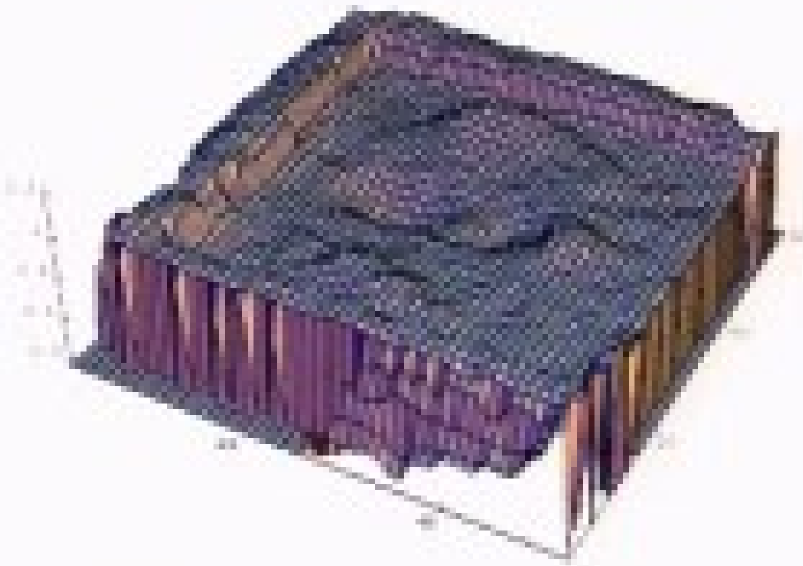
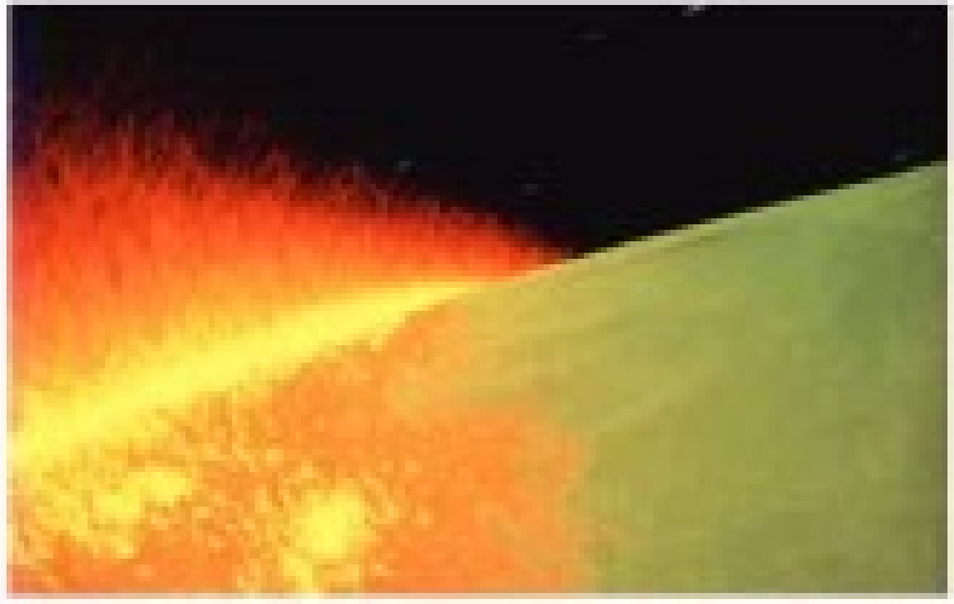


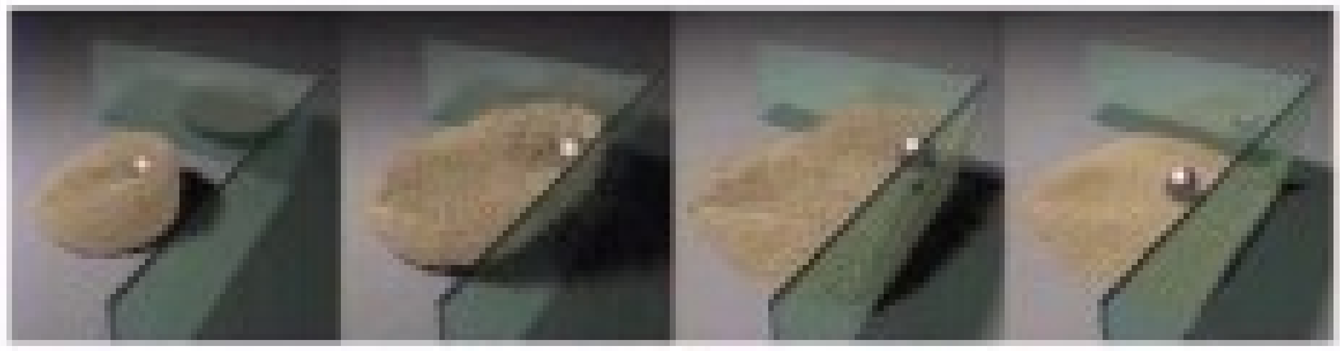
Soil simulation

- Particles
  - Graphically motivated
  - Goal: impressive visualization
  - Few physical computations
- Discrete Element Method
  - Material research
  - Goal: physical correctness
  - High computational complexity

⇒ Combine the best of both approaches



Star Trek II: The Wrath of Khan



Simulation of sand (DEM)

A single particle

Definition

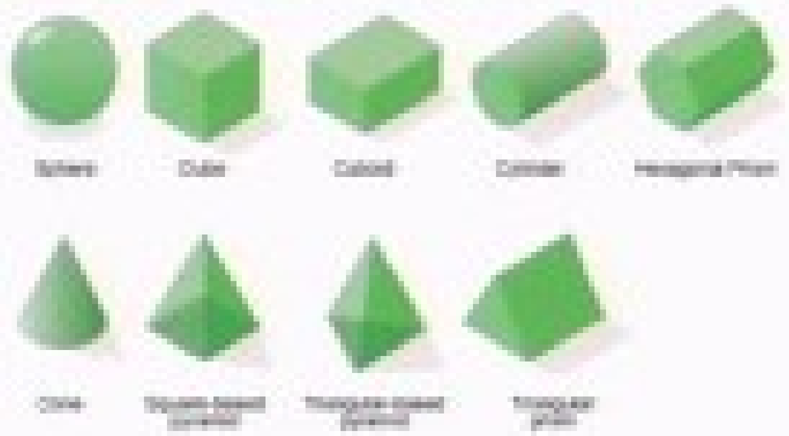
A particle represents a single point in 3D space defined by its position vector $\vec{p}$ and its tendency to move somewhere (velocity $\vec{v} = \frac{d\vec{p}}{dt}$).

Extensions

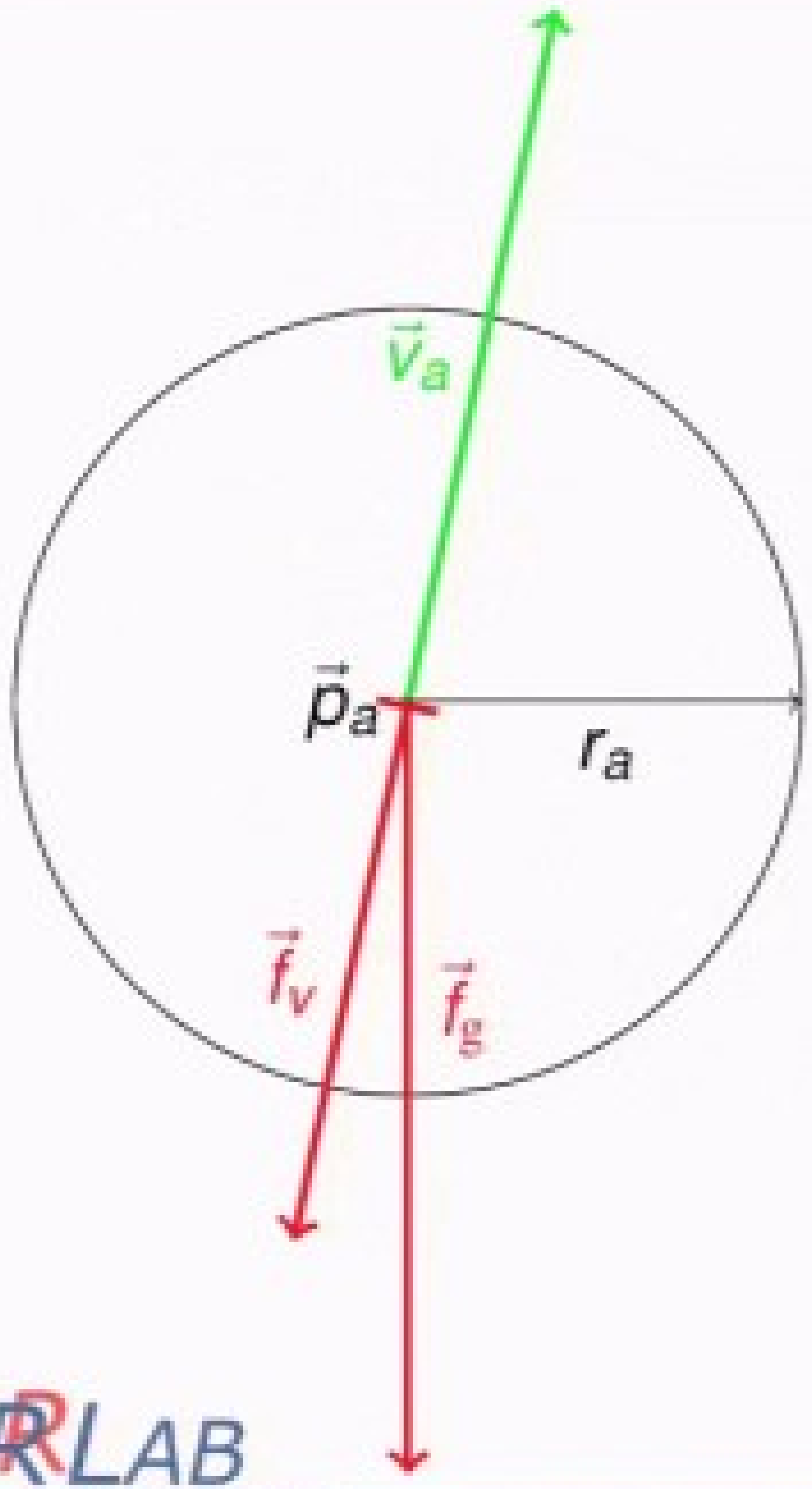
Additional abilities of the particle define its behaviour.
Two types:

- Graphically motivated
  - Colour
  - Visual shape
- Physically motivated
  - Unary: Gravity, viscous drag
  - N-ary: Forces of spatial interaction
    - Hooke's law spring
    - Attraction forces

Behaviour fusion $\Rightarrow$ force vector $\vec{f}$



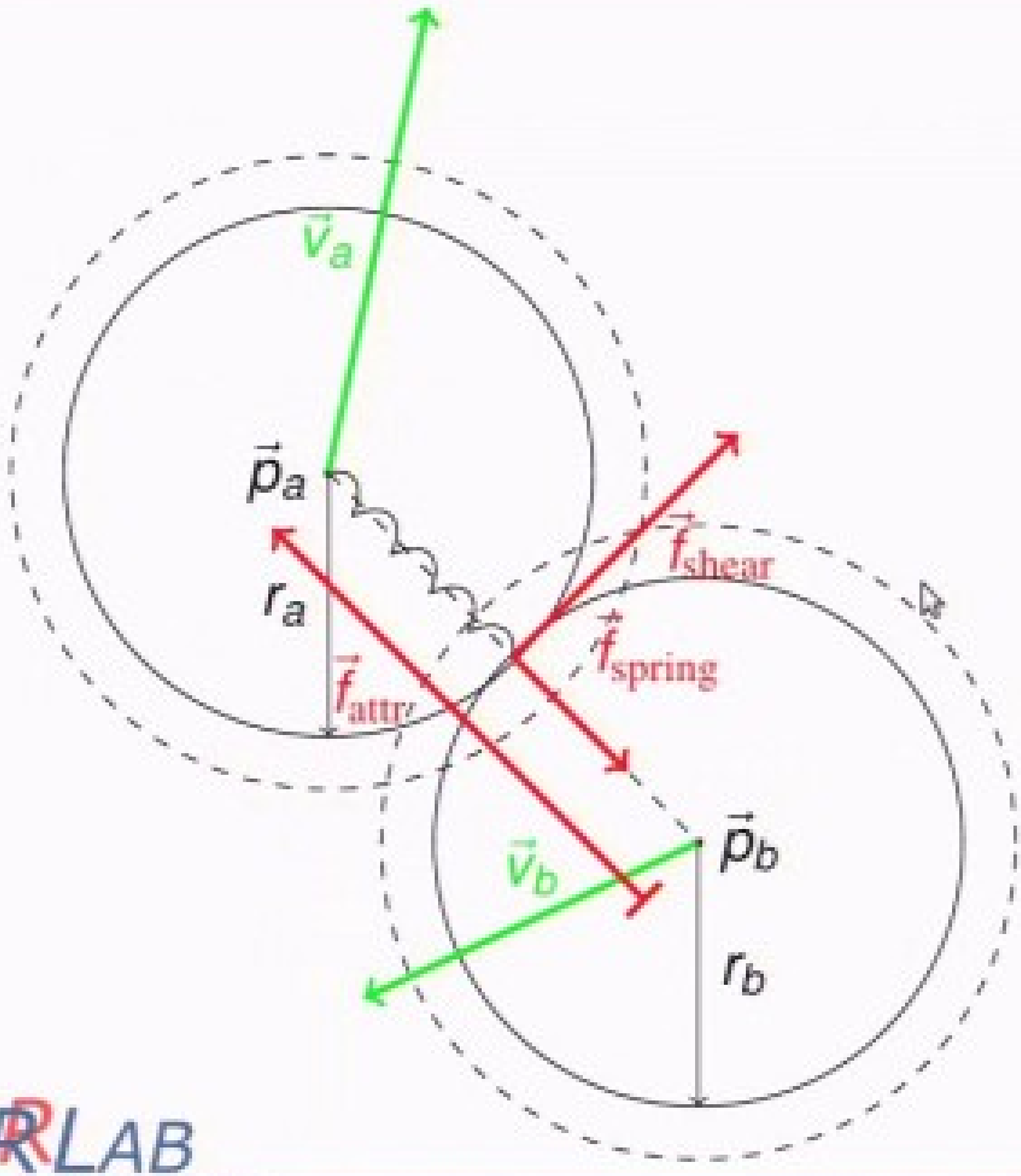
Unary forces



Unary:

- Gravity: $\vec{f}_g = m \cdot g$
- Viscosity: $\vec{f}_v = -k_d \cdot v_a$, k_d damping constant

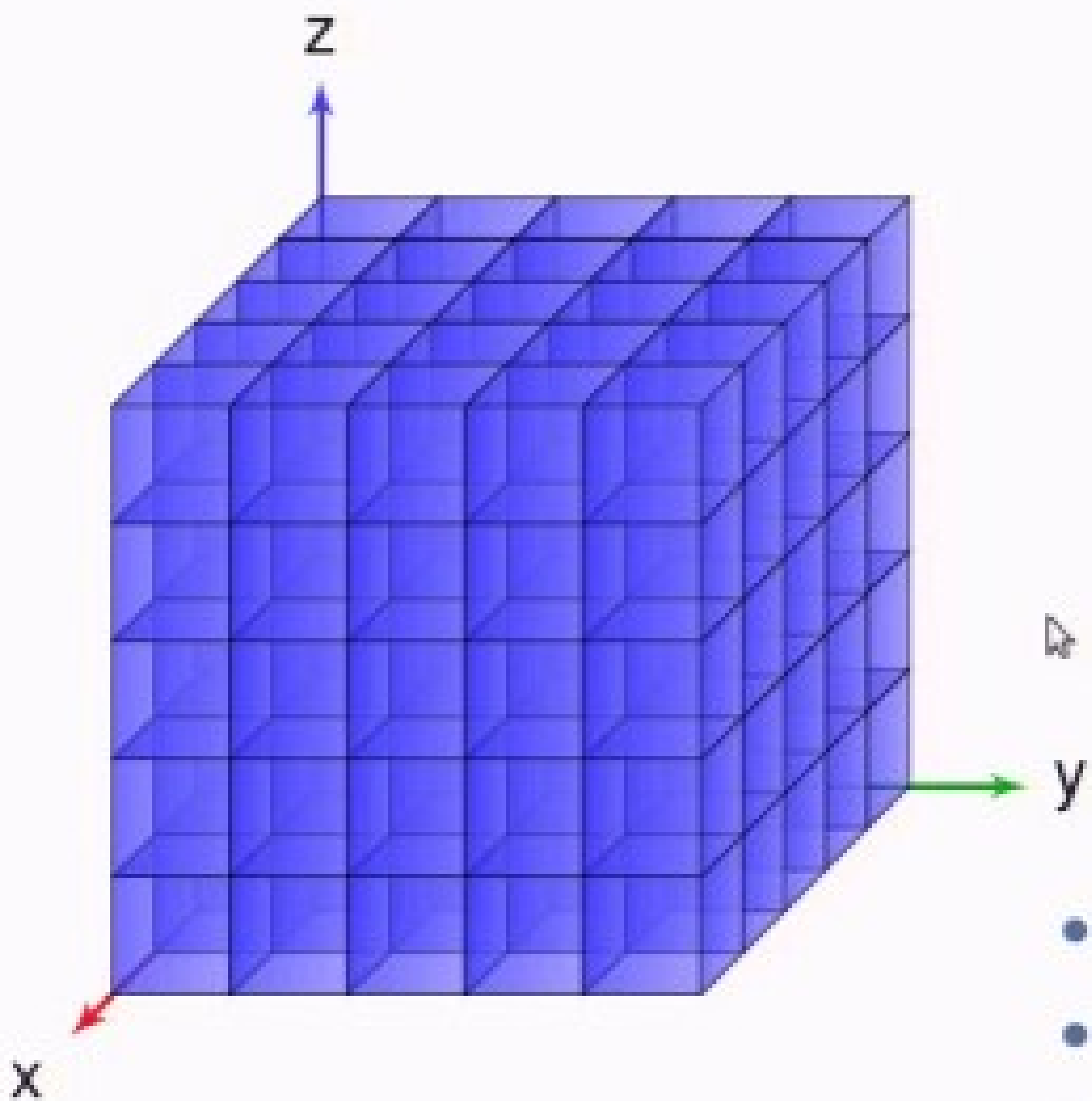
N-ary and spatial interaction

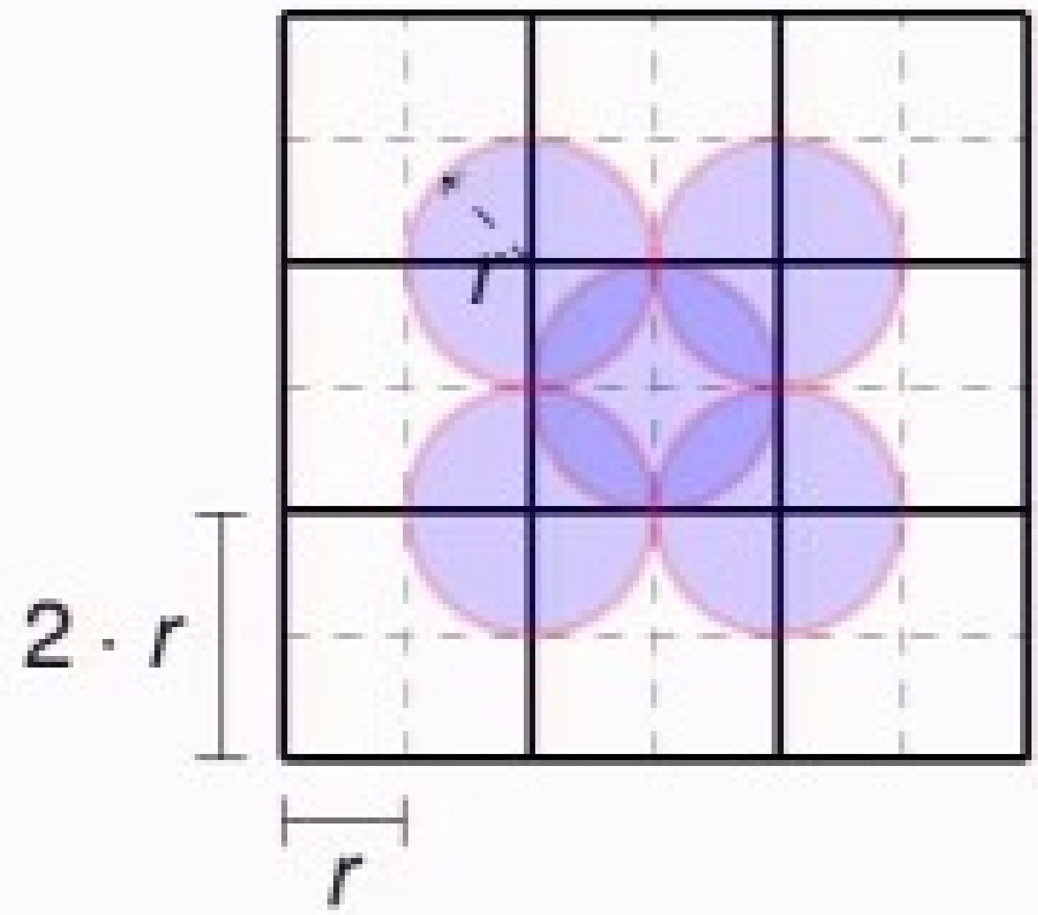


N-ary and spatial interaction:
3 forces

- Spring (longitudinal)
- Shear (transversal)
- Attraction

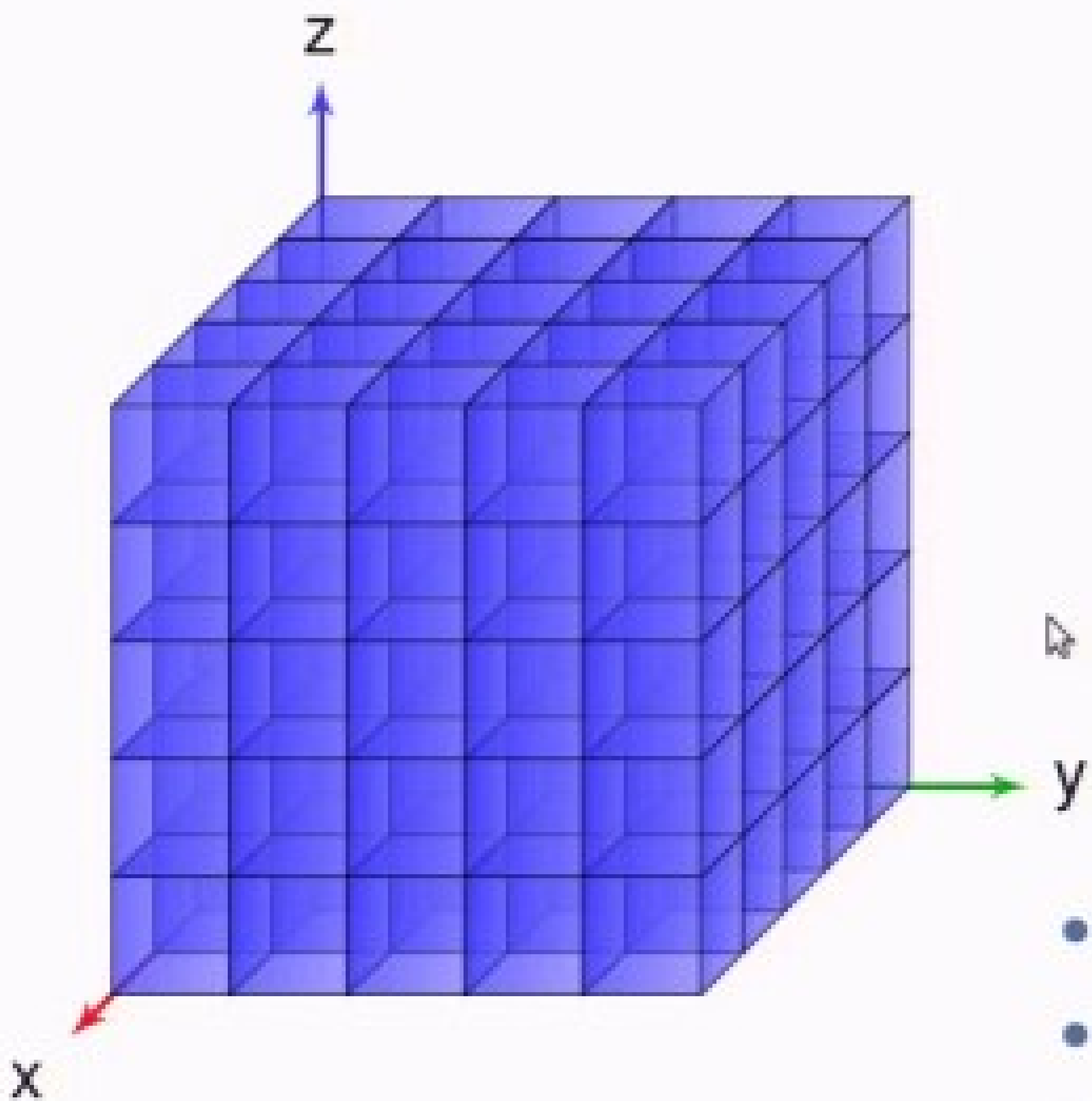
3D grid structure

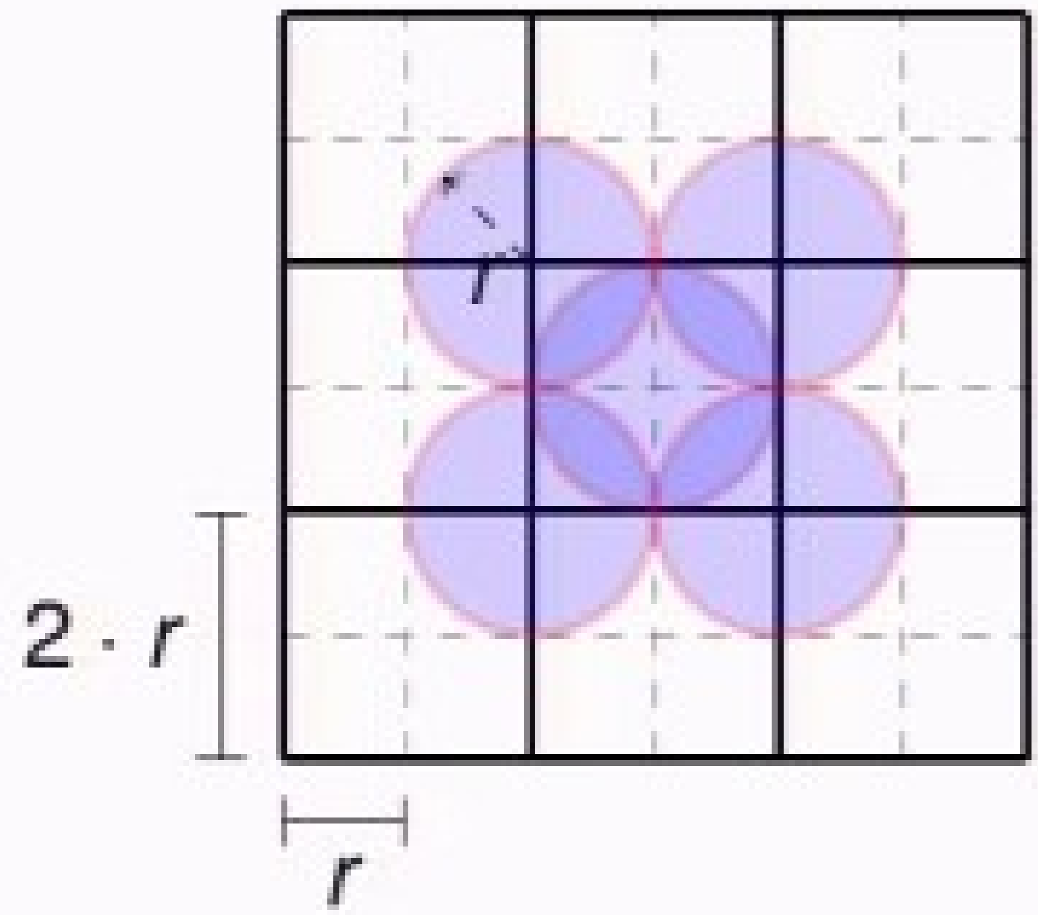




- Space divided into cubes
- Side length: diameter
- Idea: presort

3D grid structure





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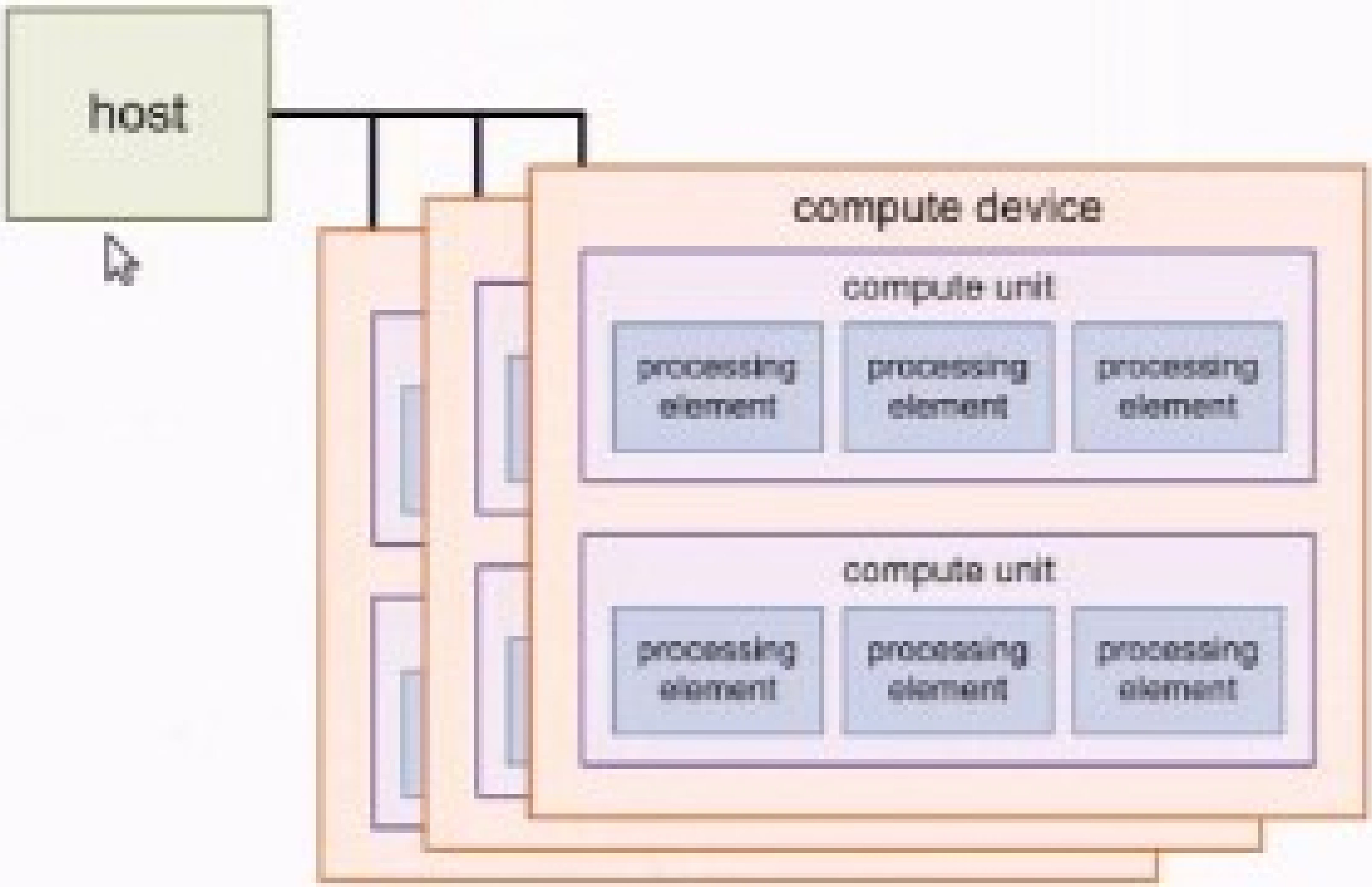
Parallel computation on graphics card

OpenCL: open, royalty-free standard for cross-platform, parallel programming



- Host: CPU
- Compute Device: GPU
- Compute unit: GPU core
- Processing element: Interaction between two particles

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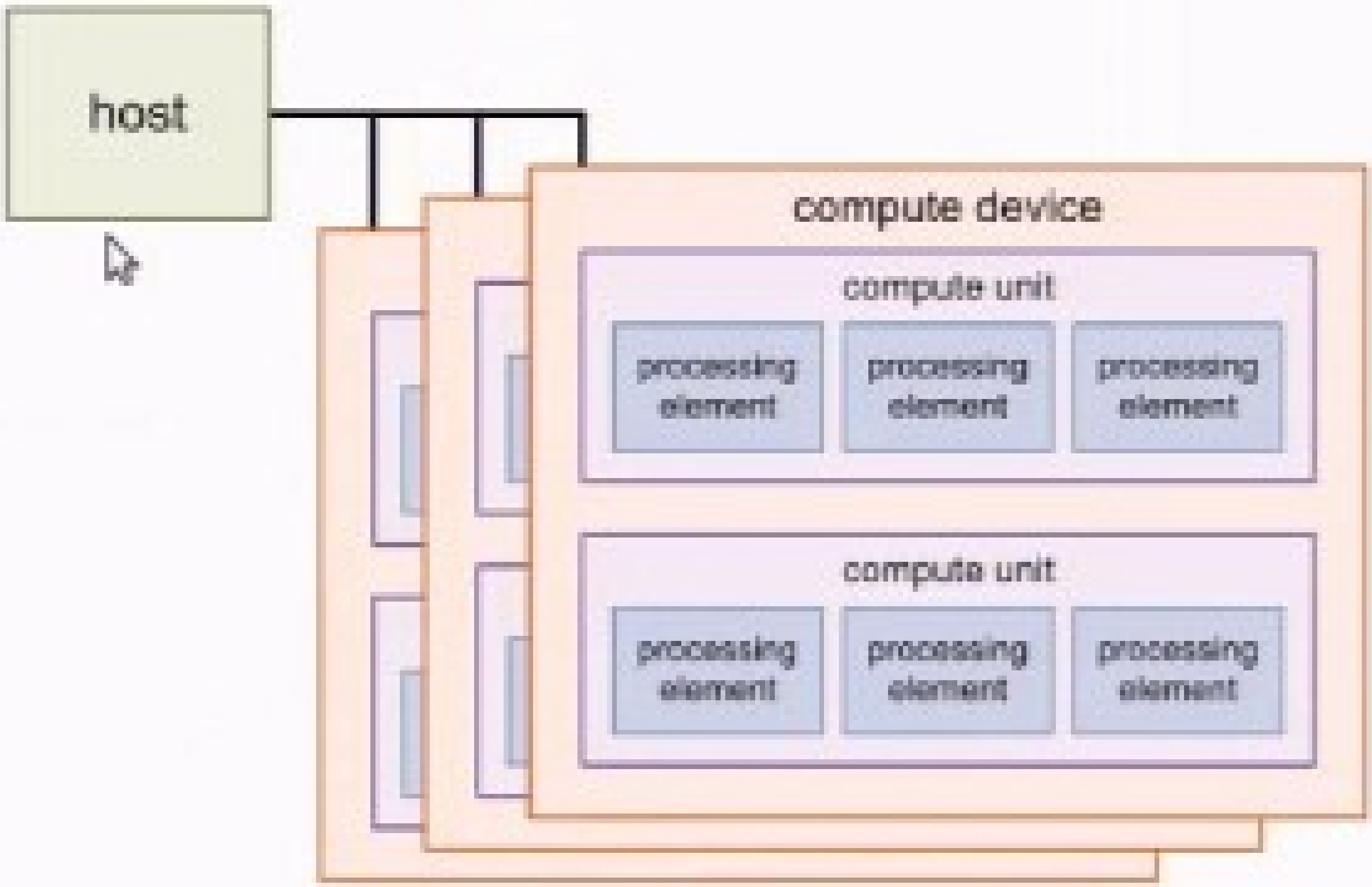
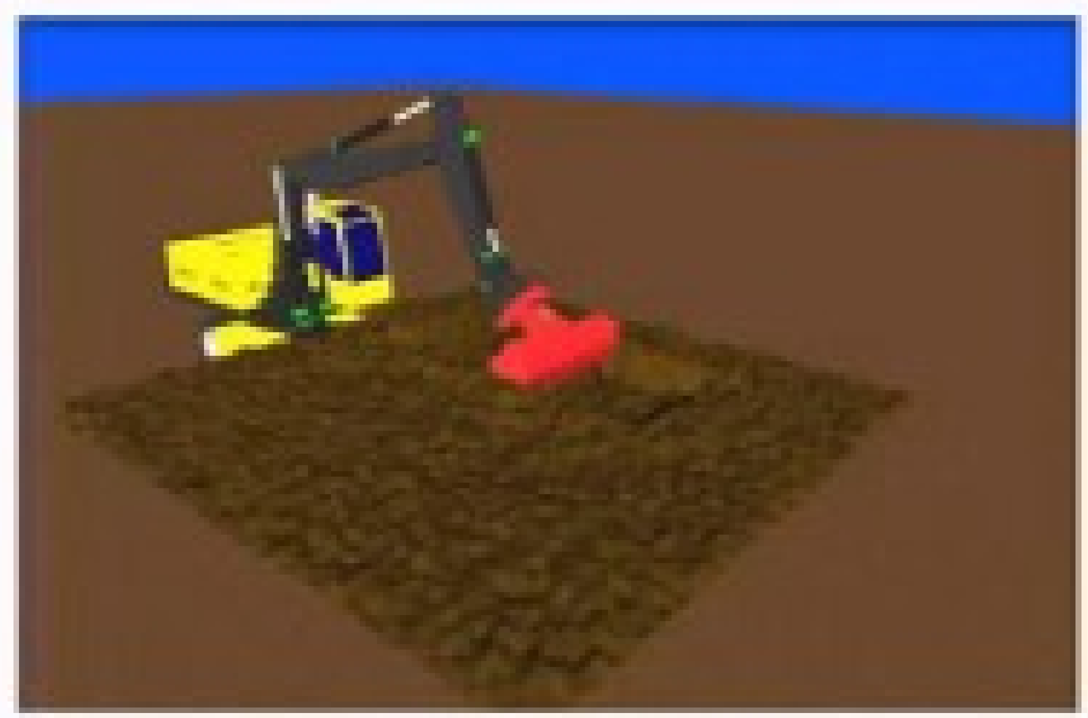


Soil simulation videos

Simulation on GPU via OpenCL

External visualisation (OpenGL)

Excavator simulation (SimVis3D)



(all videos are screen-captures and in original original speed)

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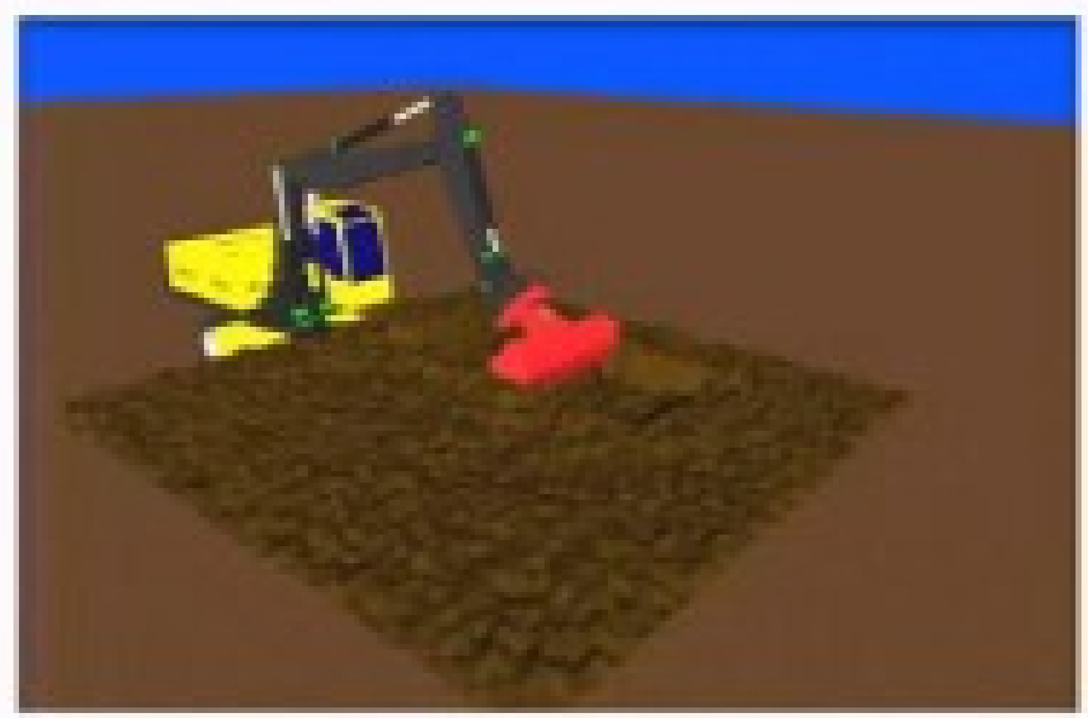

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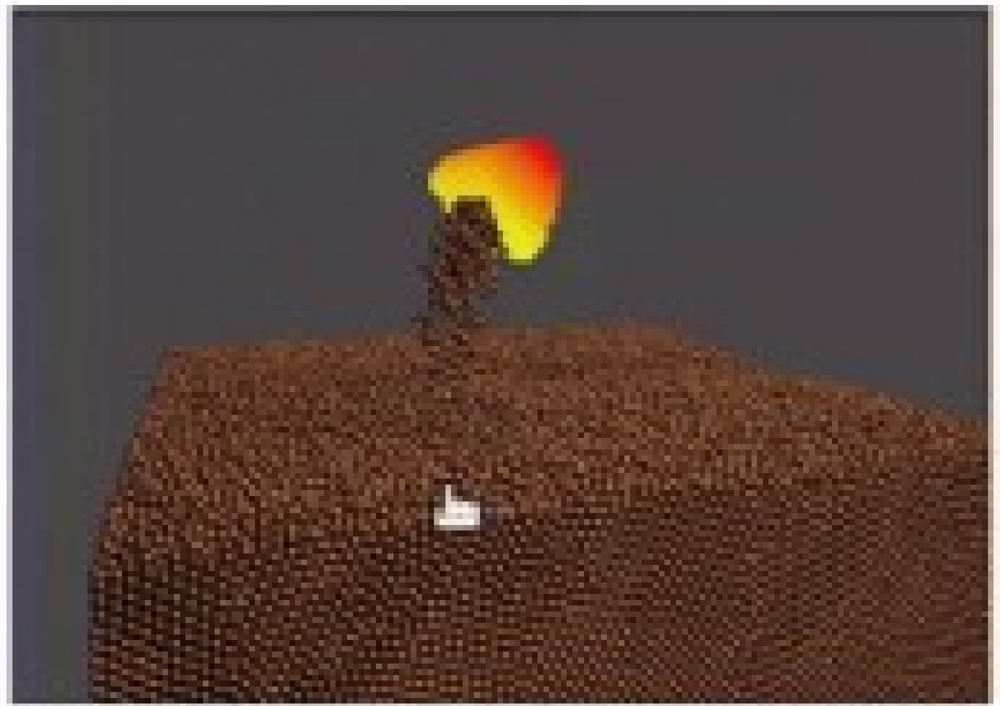

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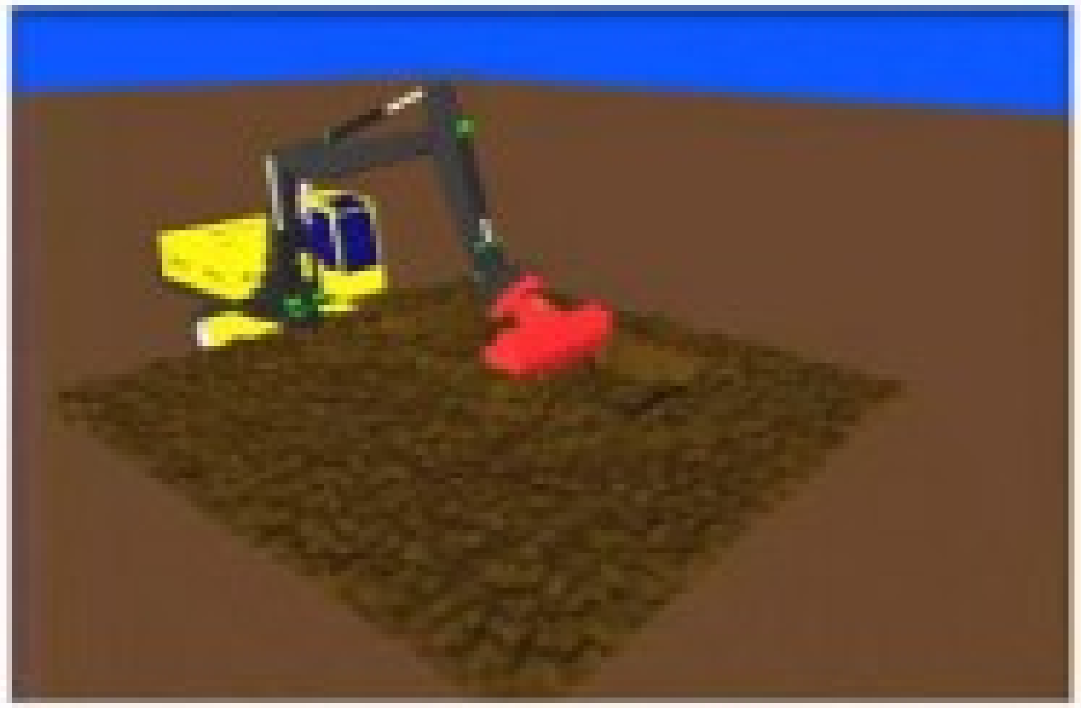

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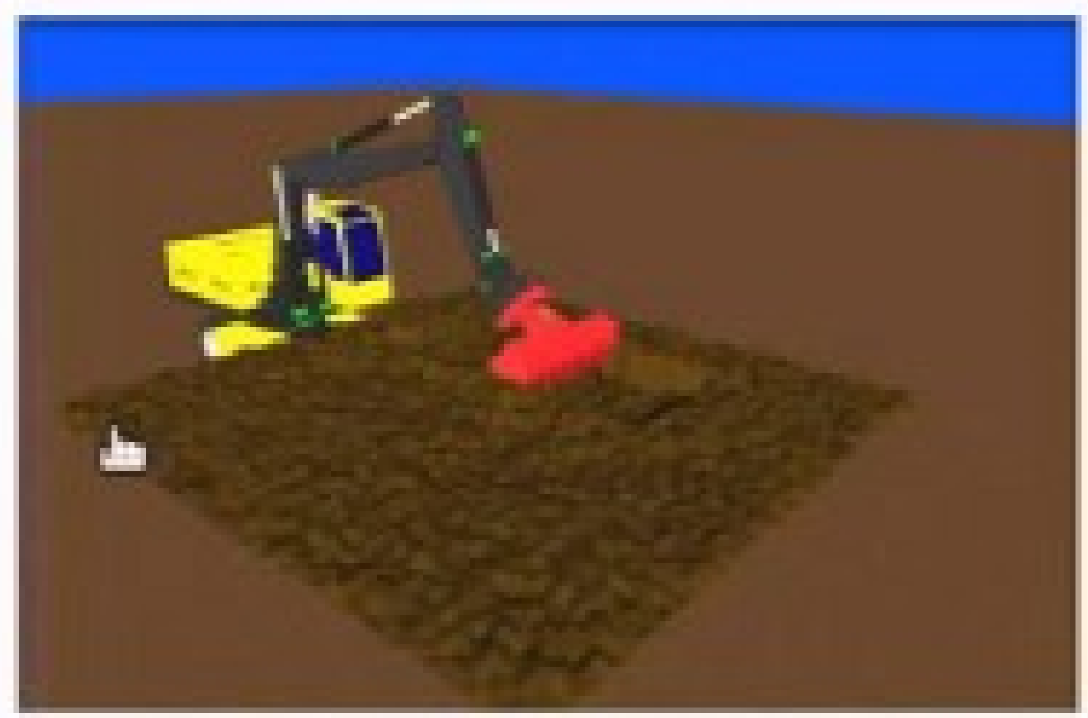
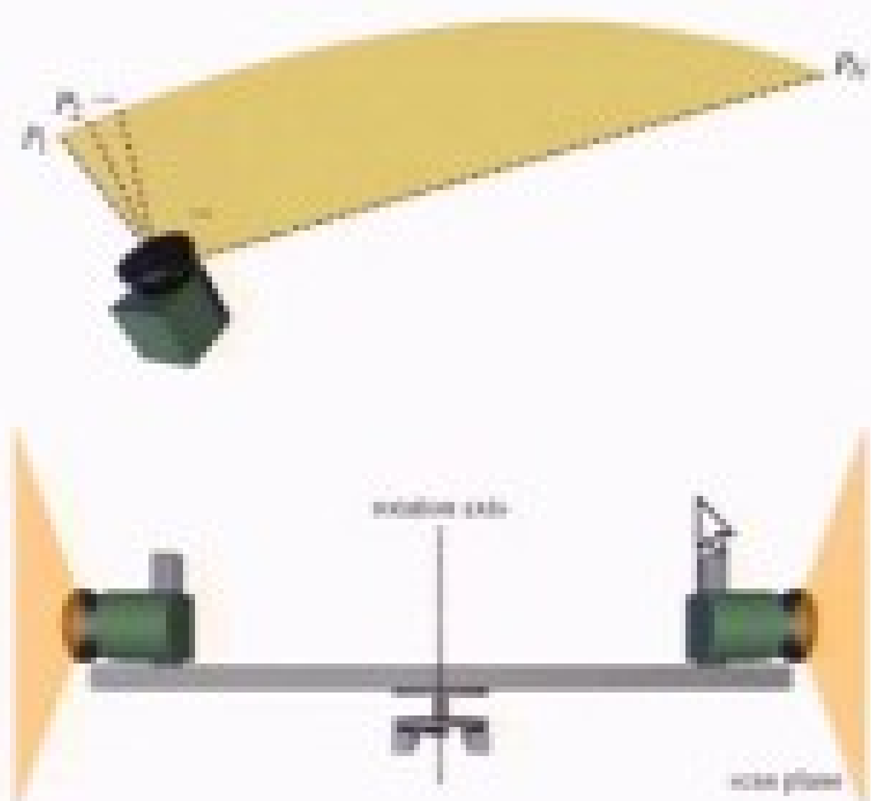
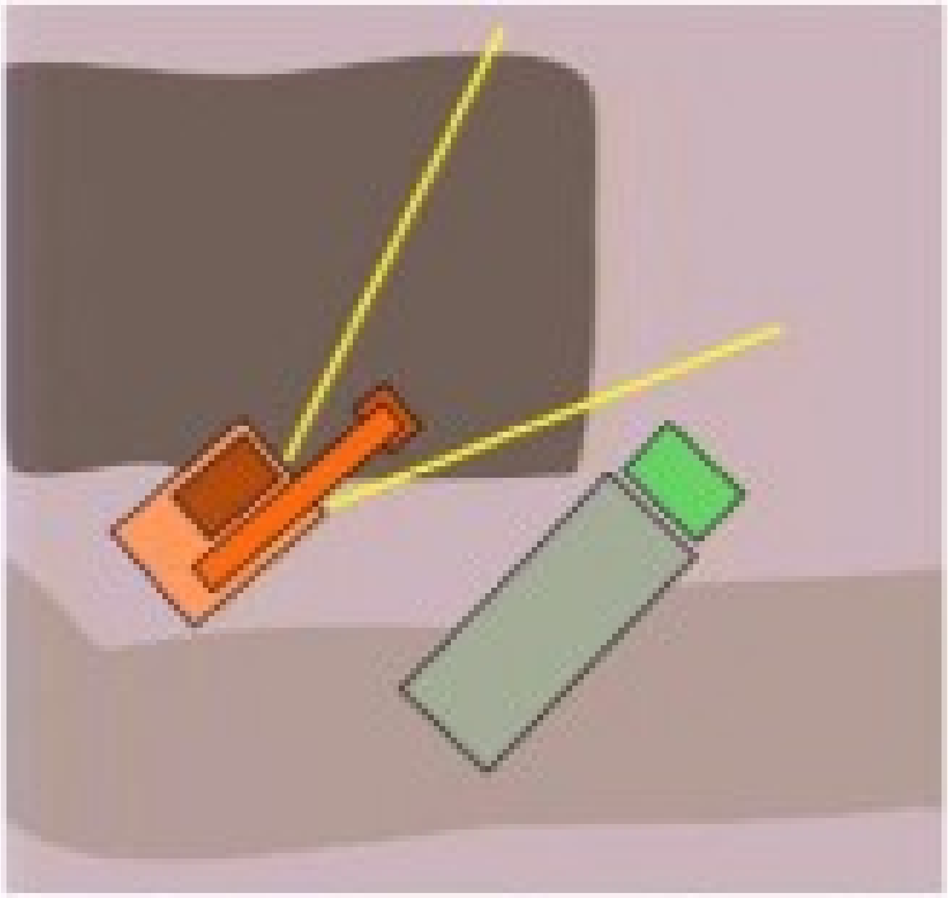


(all videos are screen-captures and in original original speed)

Gathering data from multiple sensors

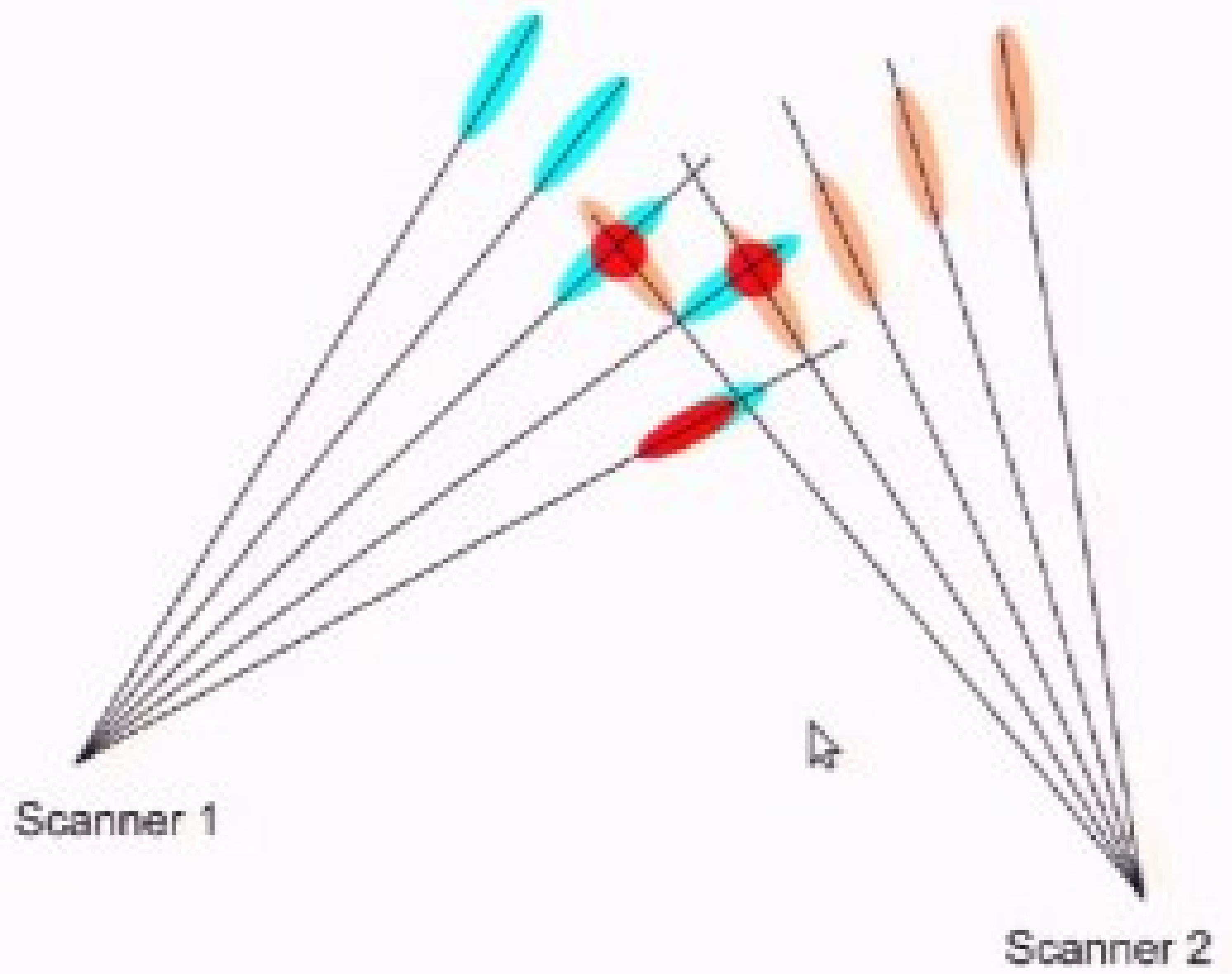
- The bucket excavator will be equipped with two planar laser scanners (left and right to the arm)
- Scanning planes are vertical
- The scanners will be used for safety and environment measuring





Strategy for handling dynamic surroundings

- Constant movement of sensors to cover wide area
- Use multiple scanners and combine data for higher accuracy:



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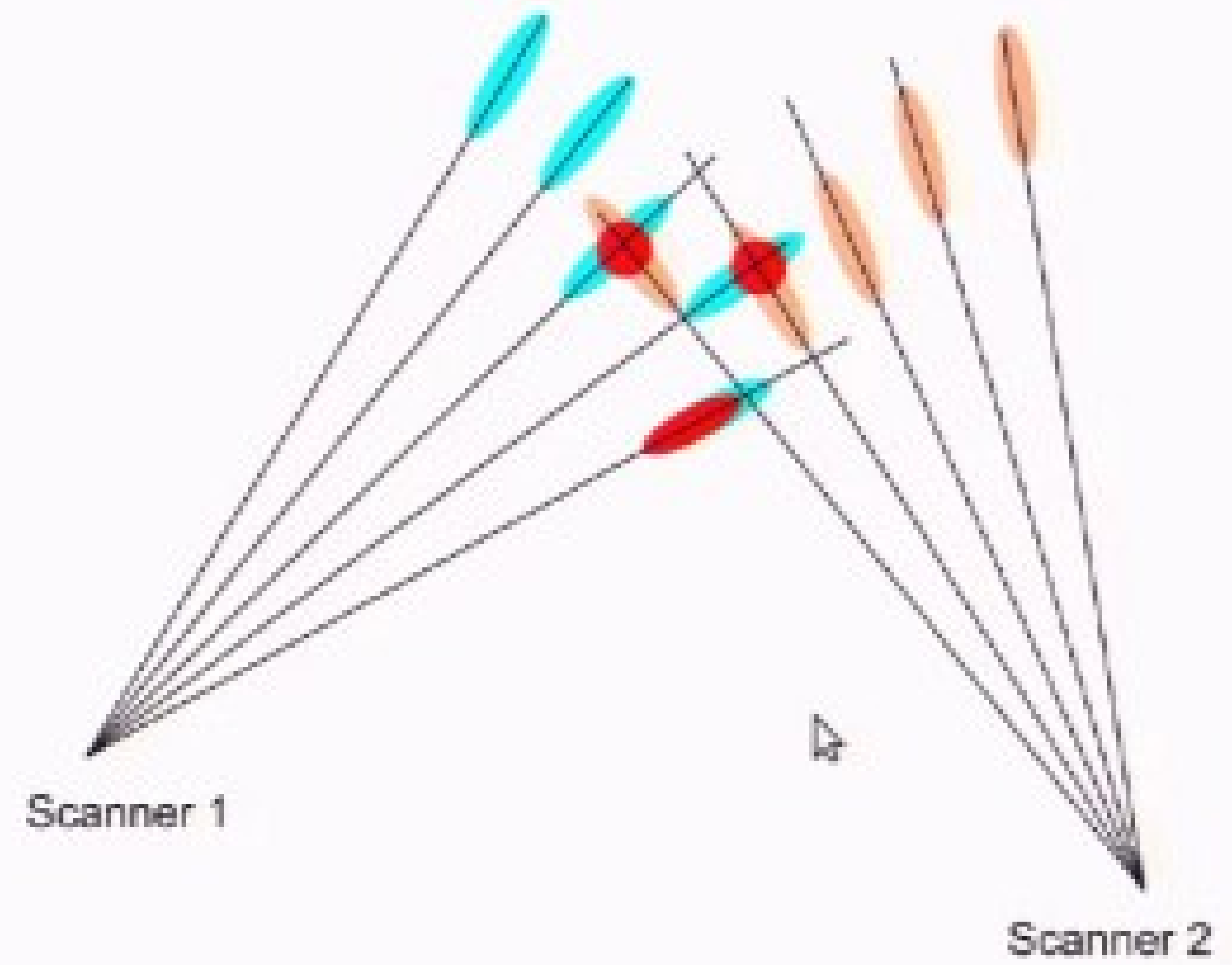
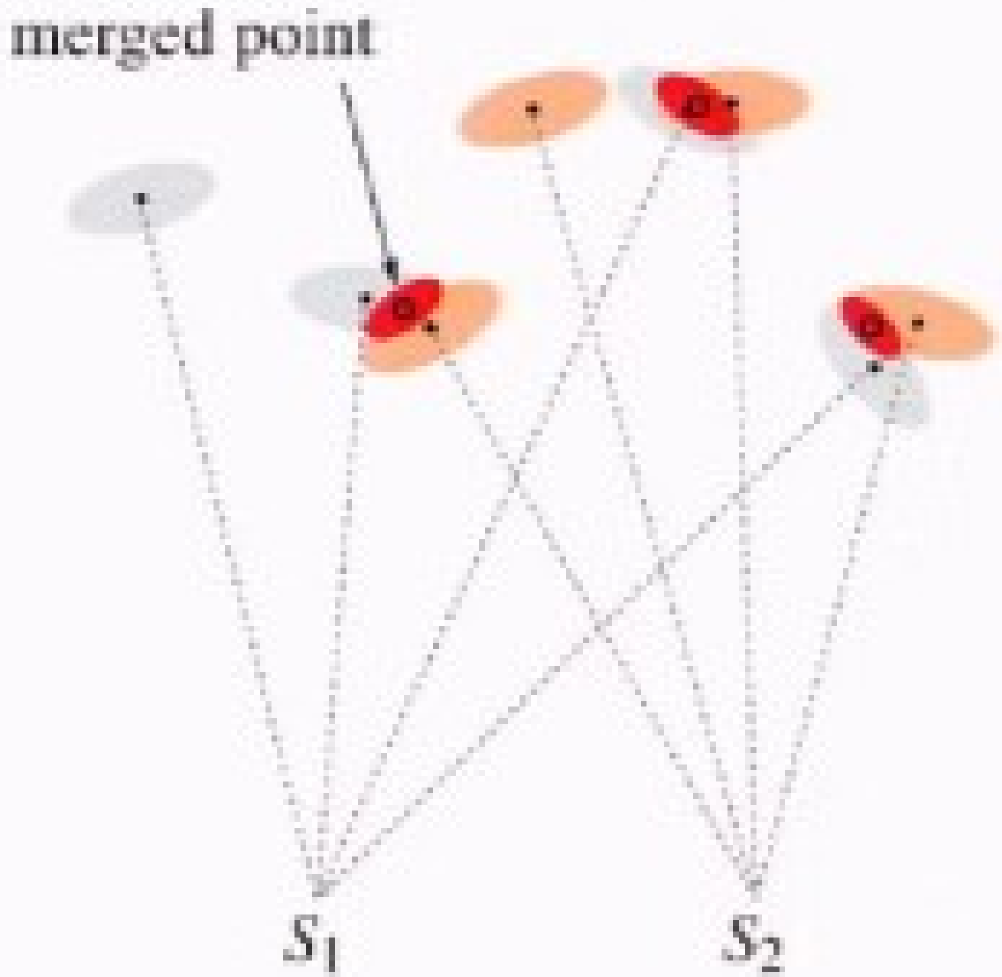
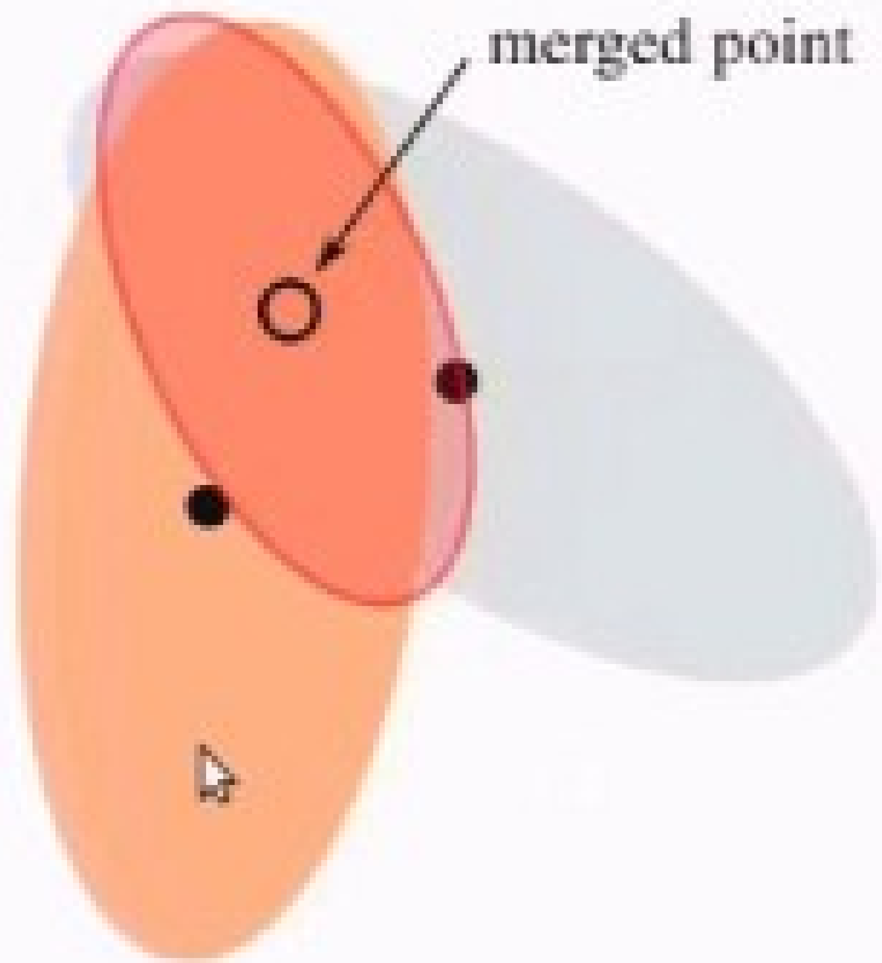


Concept: data gathering

- Point cloud: New scan points added from each scan
- Aging: Scan points “decay” and get discarded
- Merging: New points are fused with close-by neighbors





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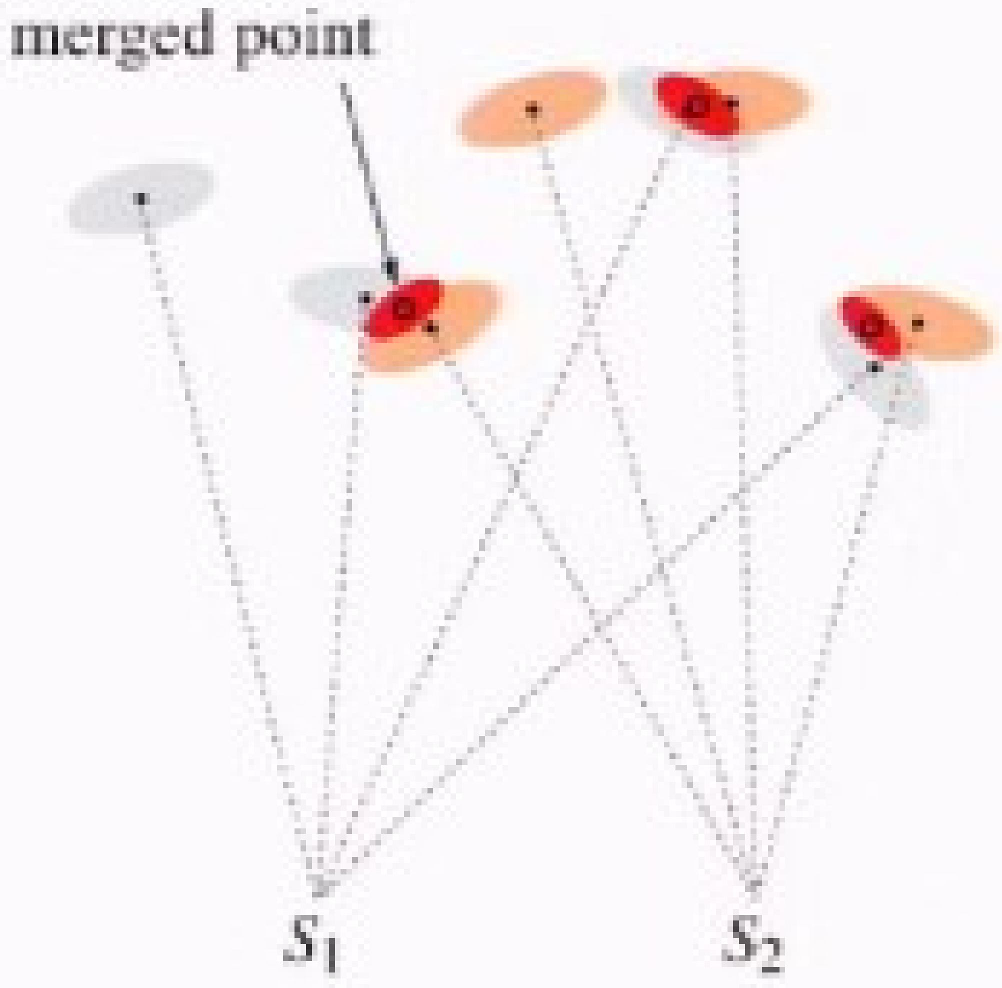
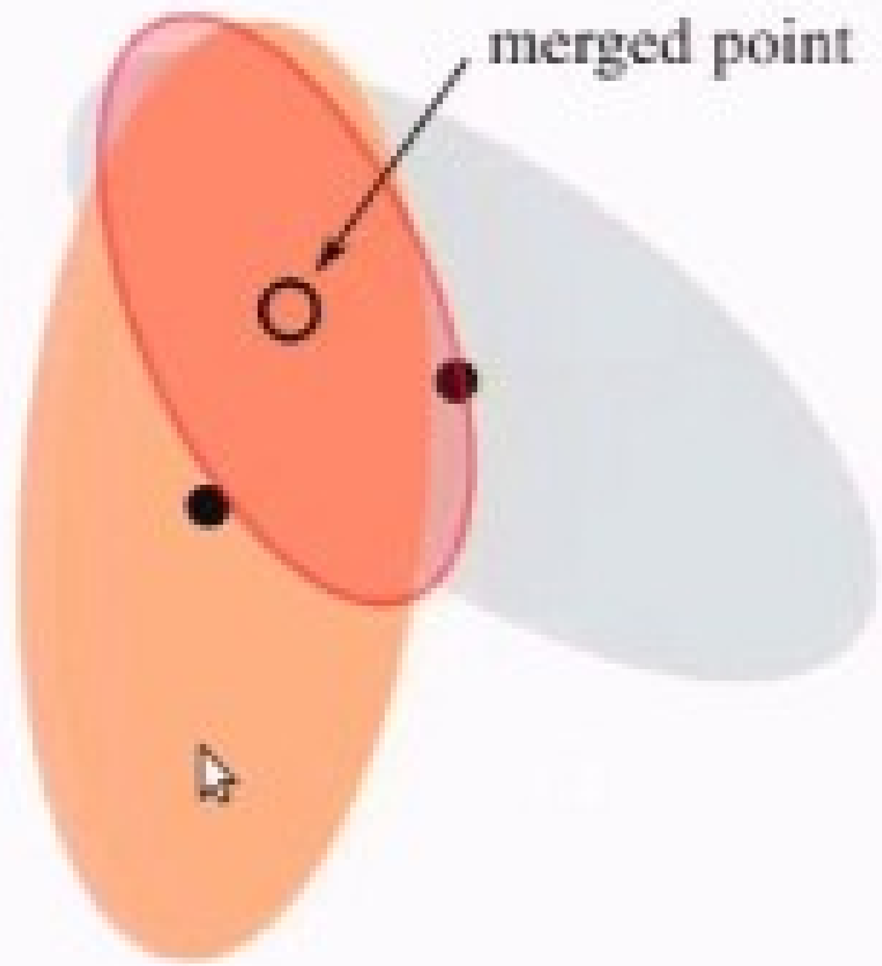


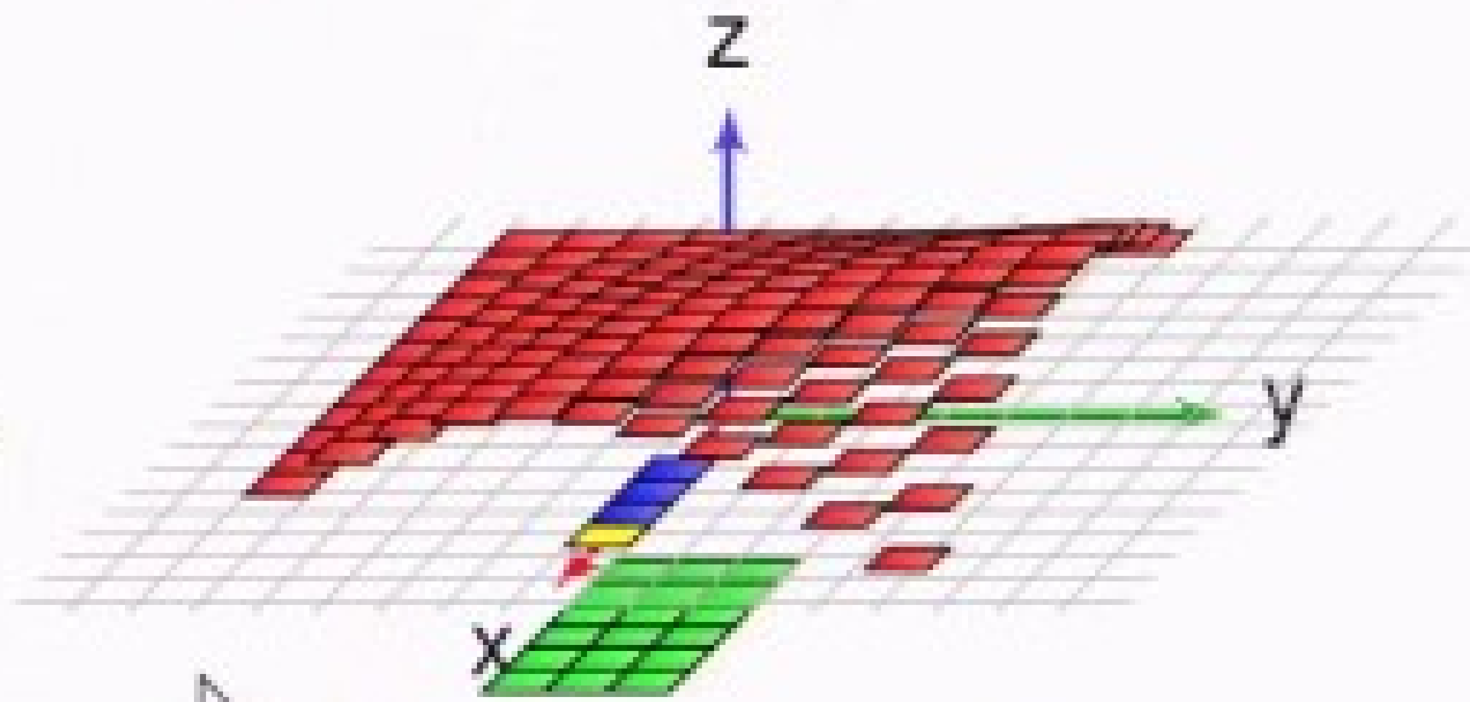


Possible excavation positions

- Red: Actual scanned surface (laser distance data)
- Green: Desired surface (generated or constructed surface)
- Blue/yellow: Chosen excavation positions

Laser point cloud

⇒



2D search grid

⇓

Cell evaluation function

Autonomous Excavator: control approach

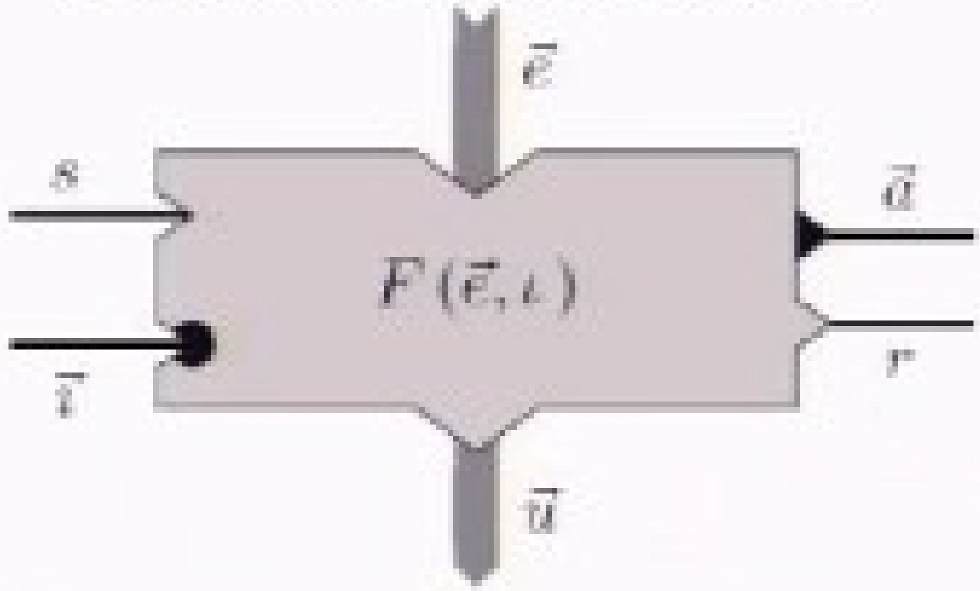
Requirements

- Compute collision free trajectories (static environment)
- Adapt to new (detected) obstacles/objects
- Perform safe movements (no tilting)

⇒ Use the adaptive behaviour-based control approach (iB2C)

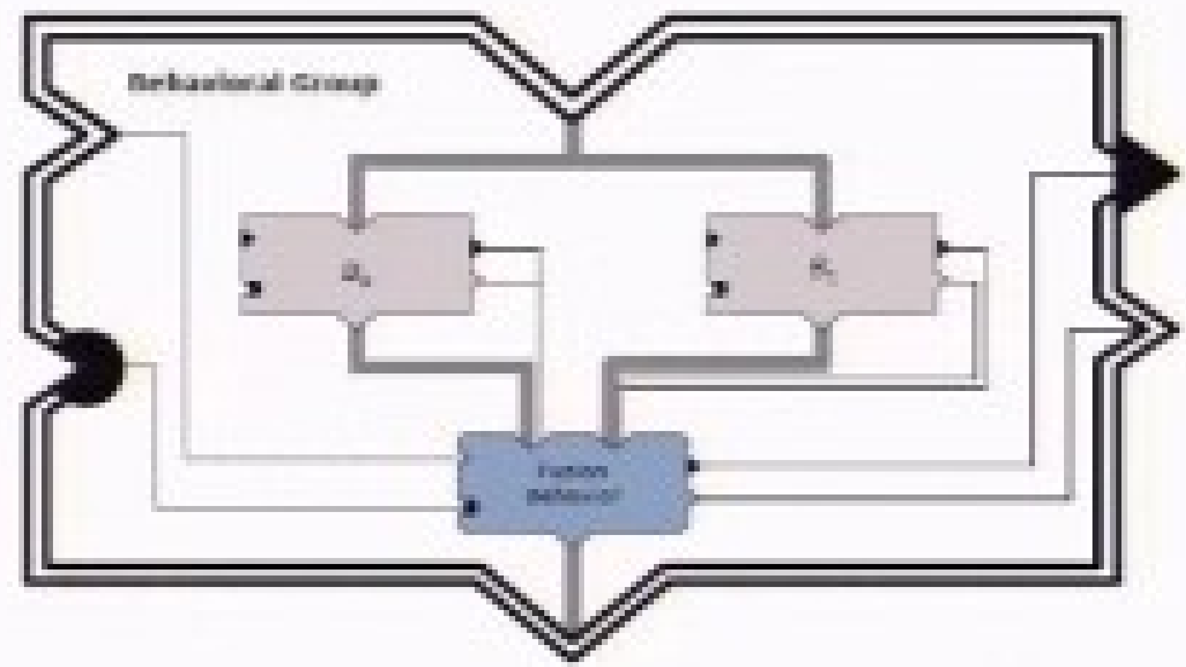
Behaviour-based control structure iB2C [Proetzsch09]

Behaviour module



- stimulation s
- inhibition $\vec{i}$
- activity $\vec{a}$
- target rating r
- input vector $\vec{e}$
- output vector $\vec{u}$

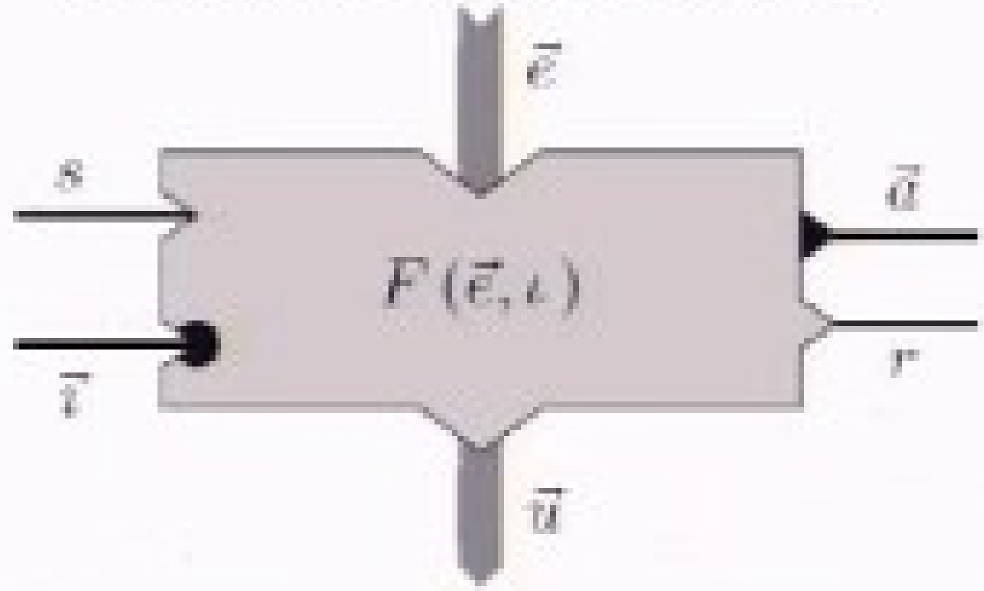
Behaviour Networks
Fusion module



- Maximum fusion
- Weighted fusion
- ...

Behaviour-based control structure iB2C [Proetzsch09]

Behaviour module



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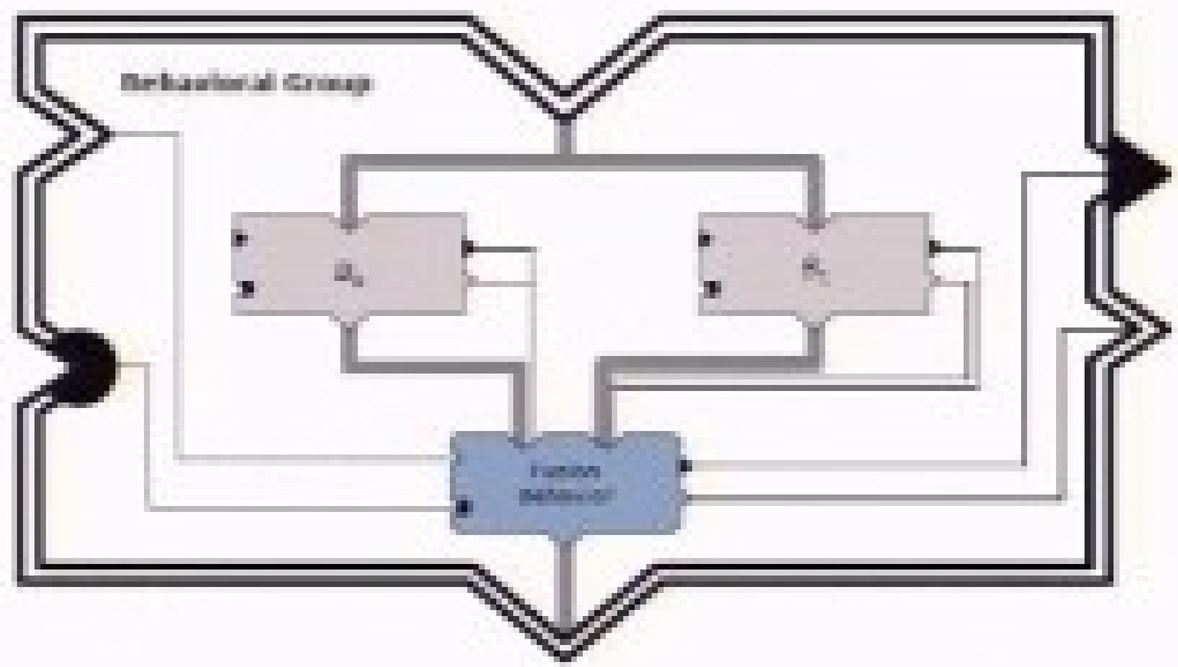
Behaviour Networks Fusion module



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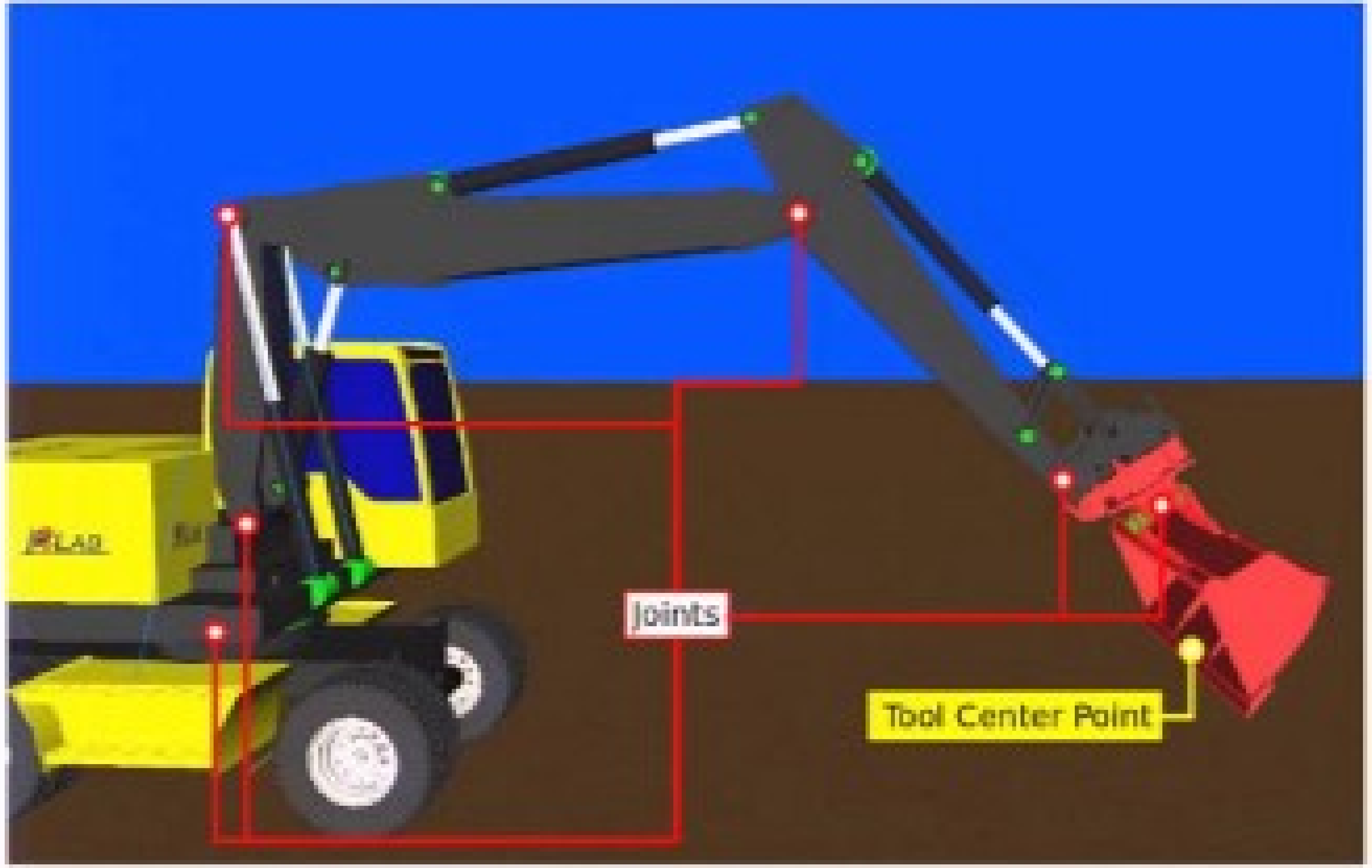
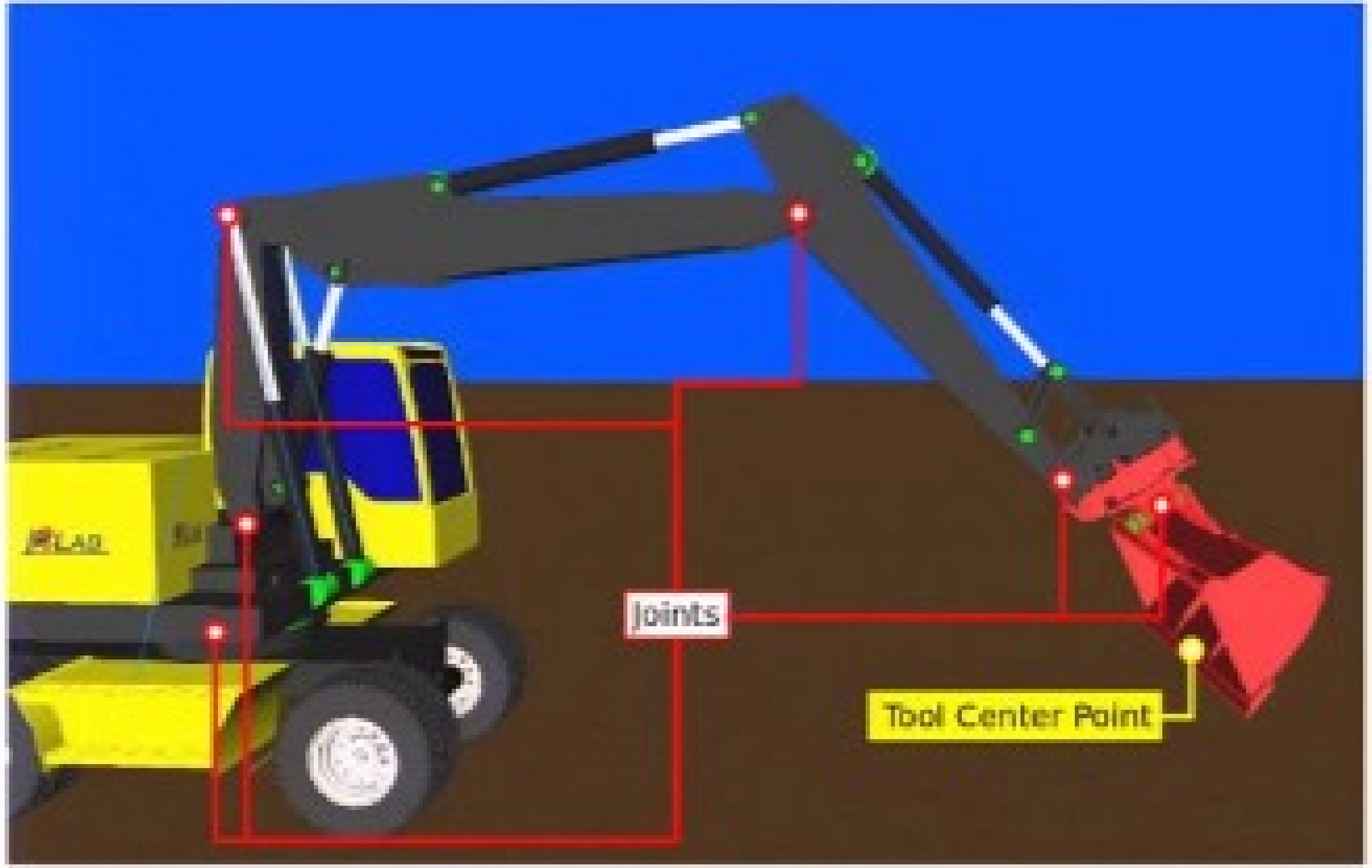
Behaviour-based inverse kinematics solver



Inverse Kinematics

Find an appropriate set of joint angles which lead to a desired pose of the Tool Center Point (TCP)

Behaviour-based inverse kinematics solver



Inverse Kinematics

Find an appropriate set of joint angles which lead to a desired pose of the Tool Center Point (TCP)

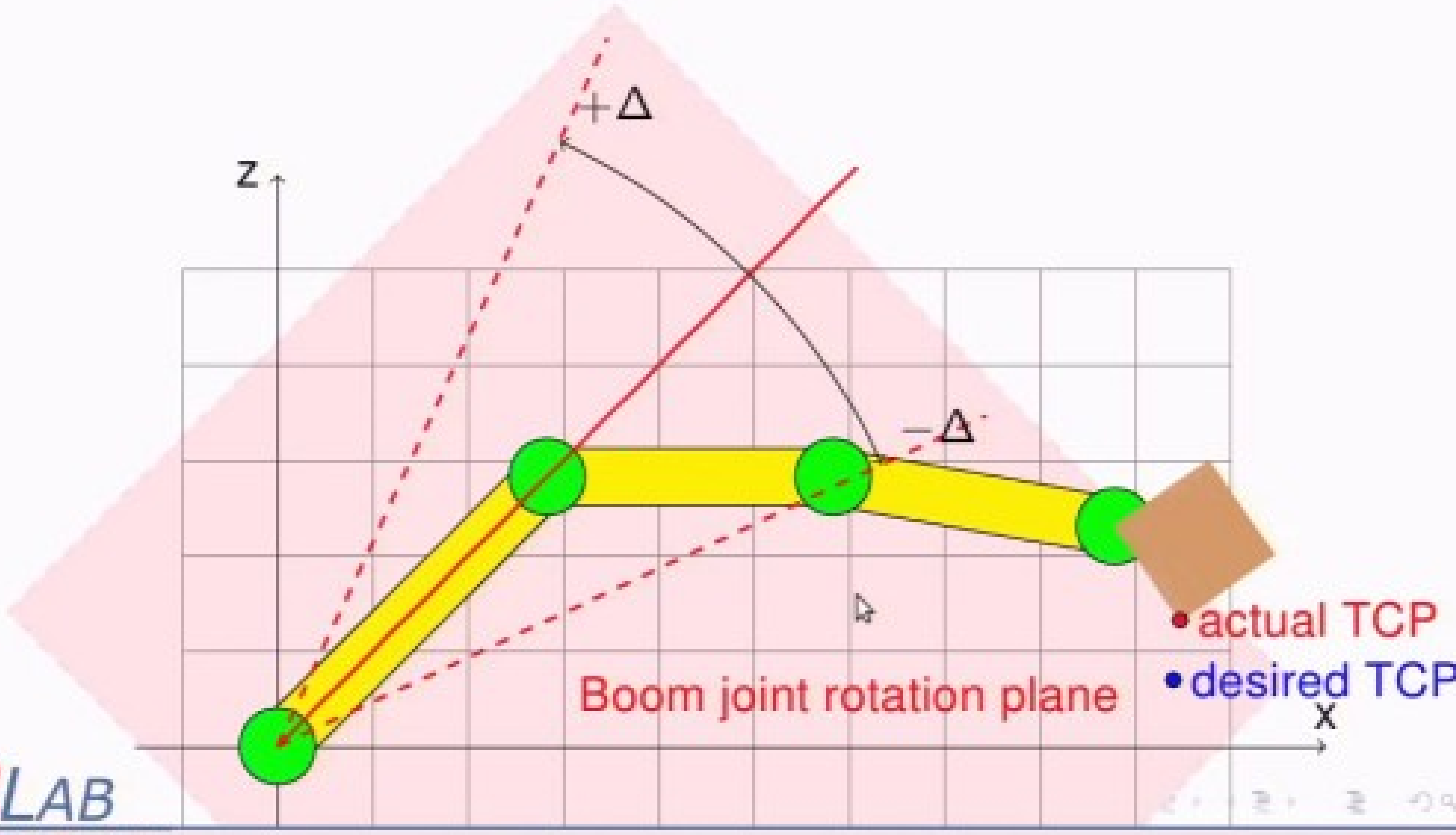
New idea

Biologically motivated approach

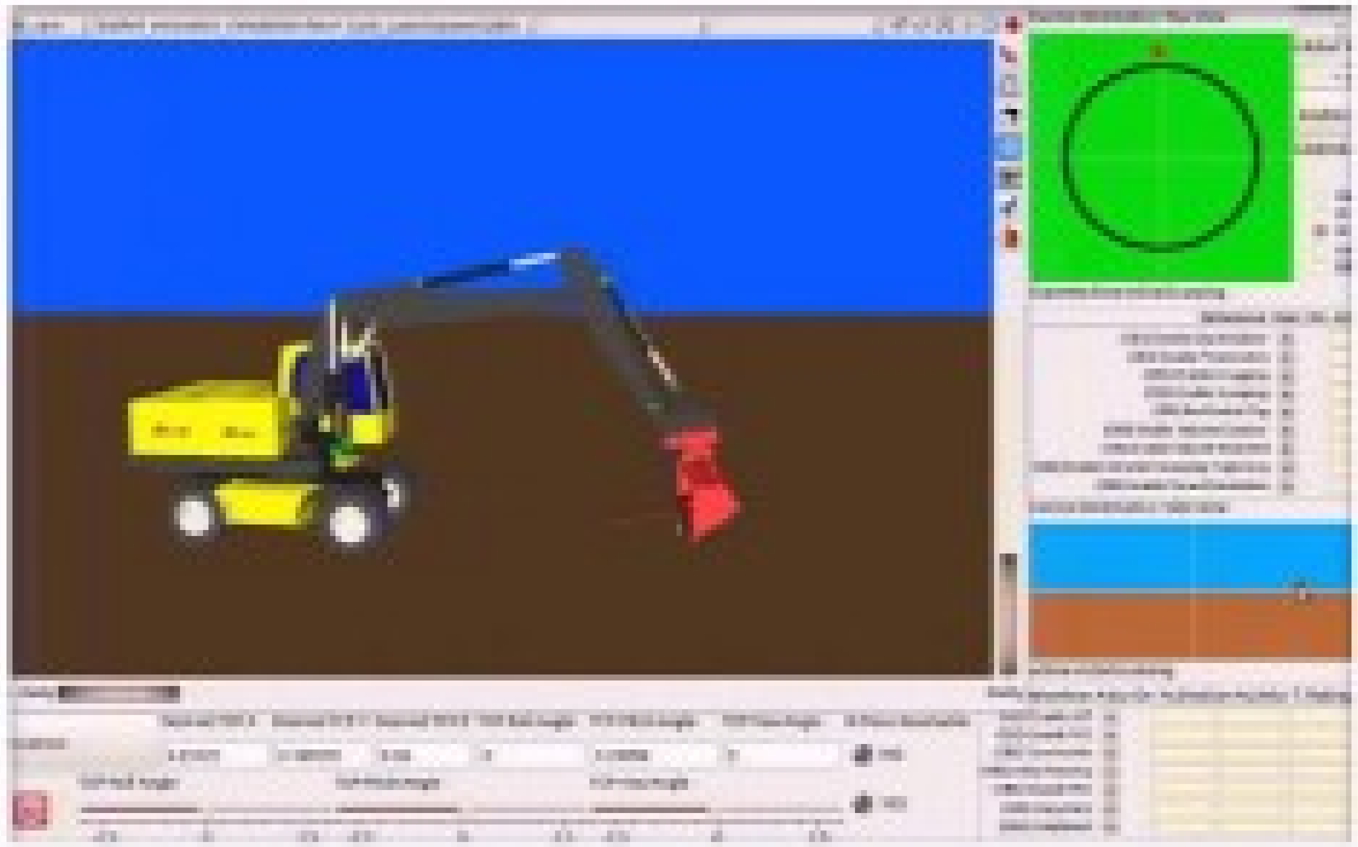
- Adaptive control (behaviour-based)
- Arbitrary kinematic chains
- Computational efficient
- Linear computational increase per joint
- Distinct interface for movement constraints

Task for a single joint per step

Rotation direction (+/-) and delta (Δ) to reach desired TCP



Operation videos



Simulated bucket excavator

Real excavator loading a truck

"All videos in normal speed - no time adjustment done".

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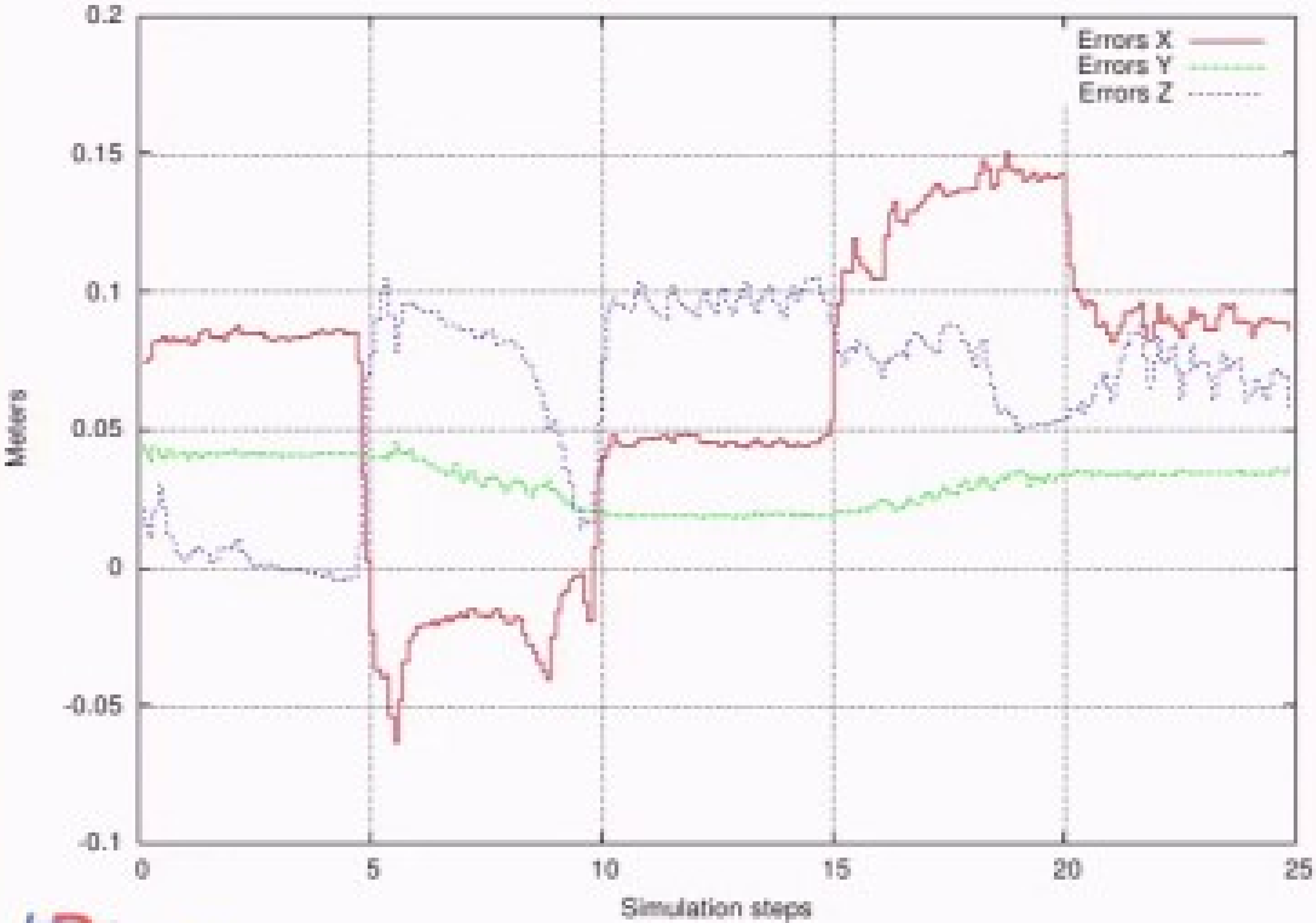
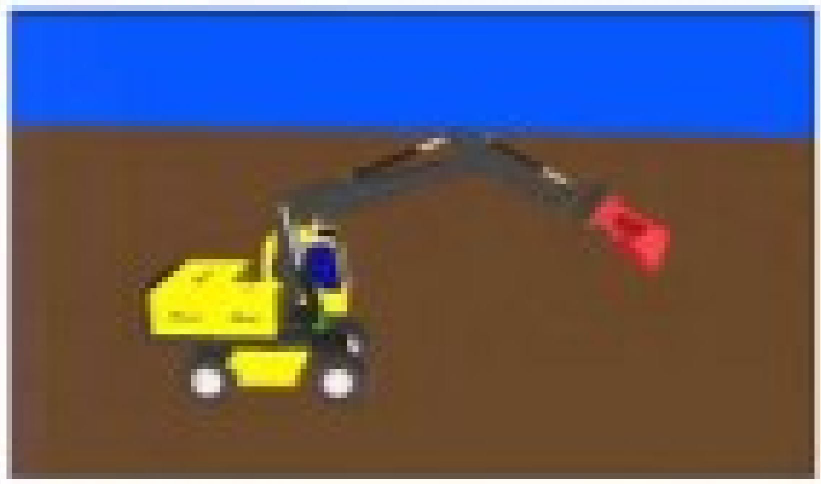
Trajectory runtime precision

Differences between the desired and achieved TCP coordinates during running a trajectory:





⇒ Maximum absolute distance error $< 0.16\mathrm{m}$

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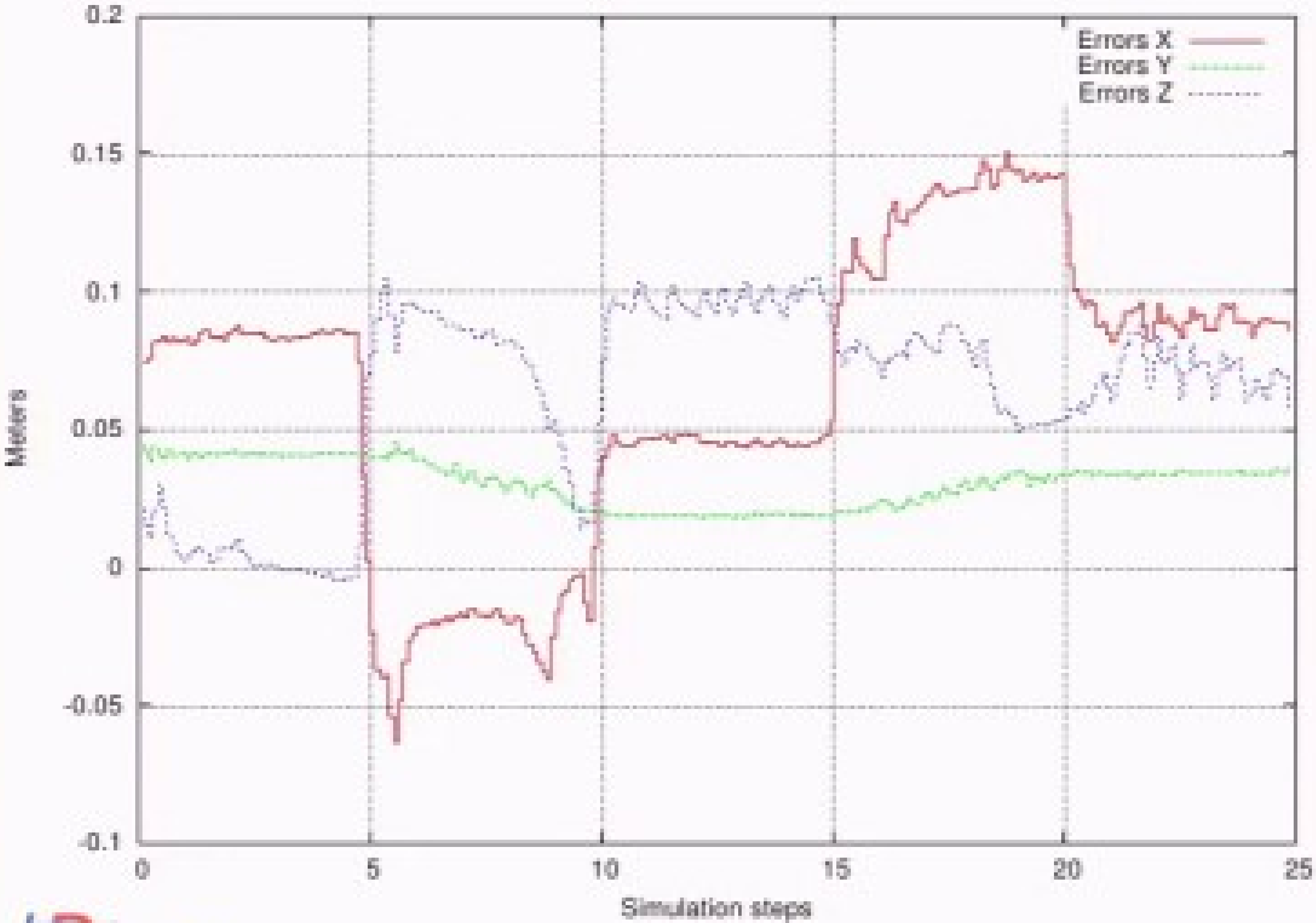
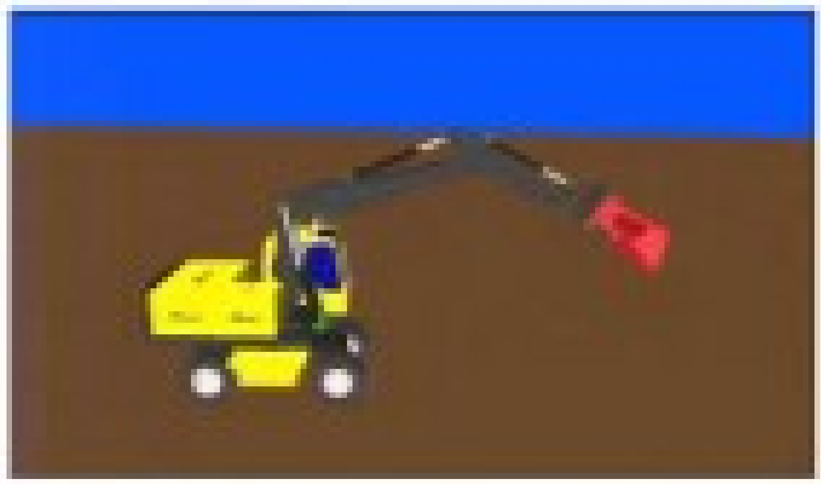
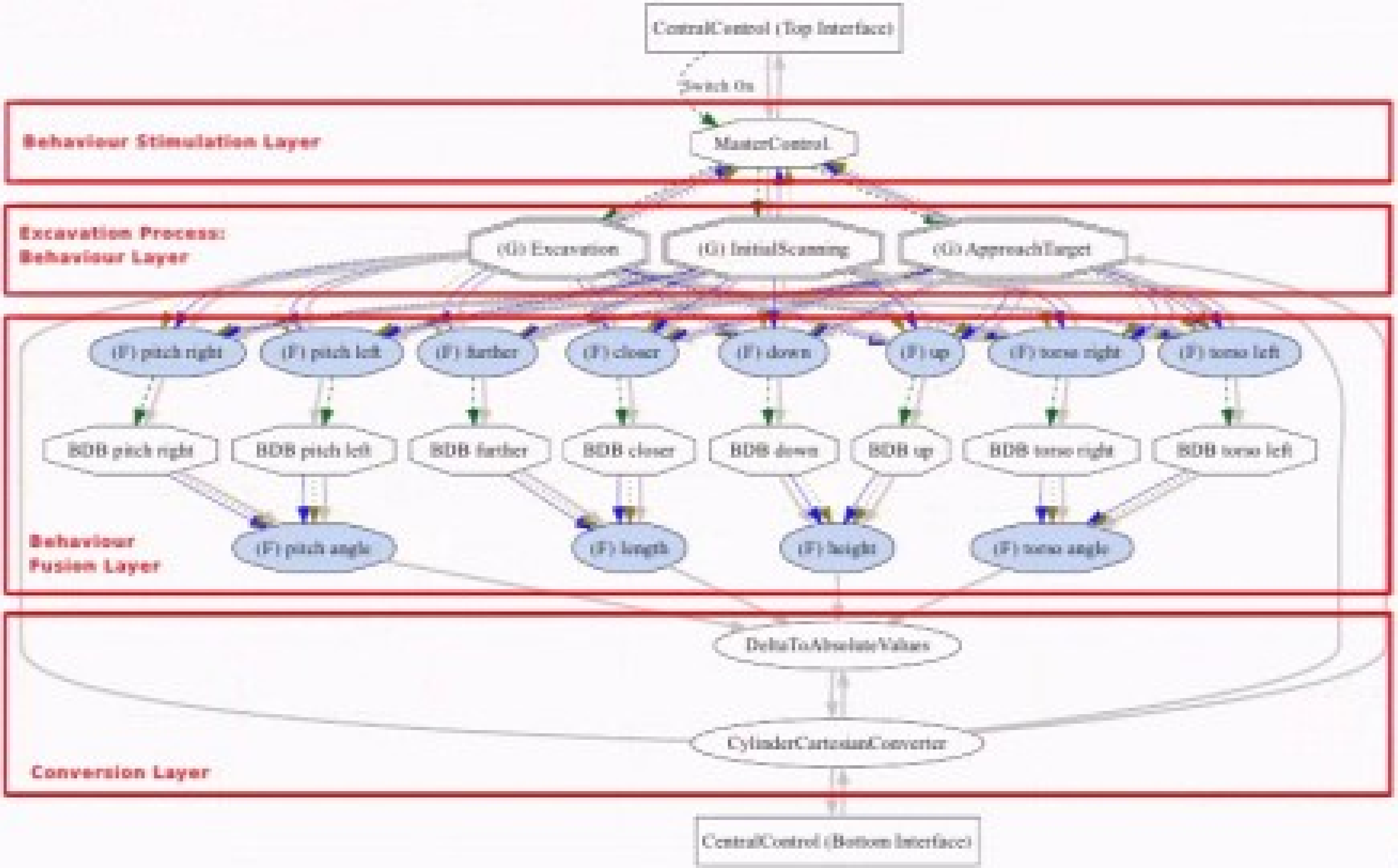
Differences between the desired and achieved TCP coordinates during running a trajectory:





$\Rightarrow$ Maximum absolute distance error $< 0.16\text{m}$

Complete system: behaviour layers



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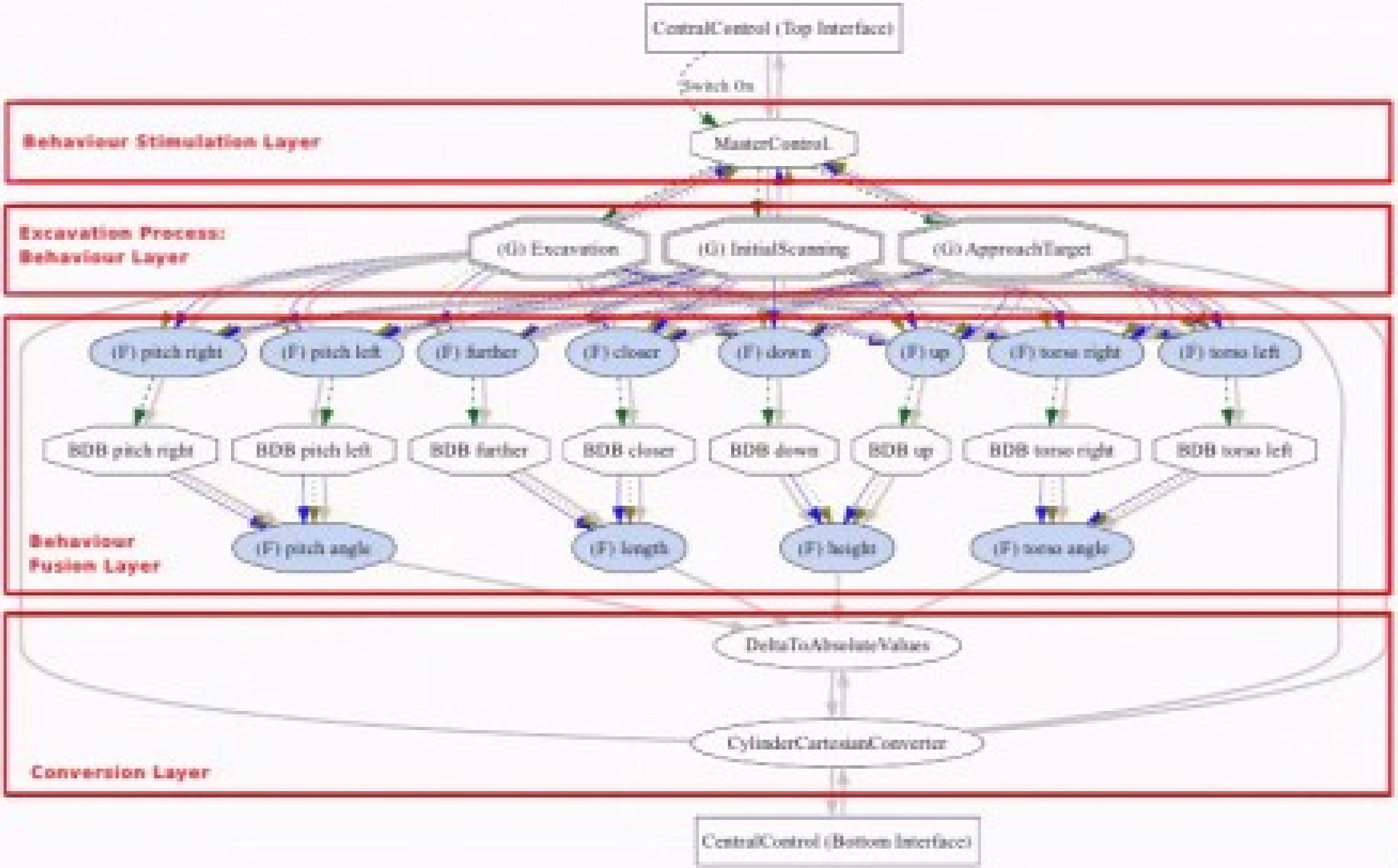
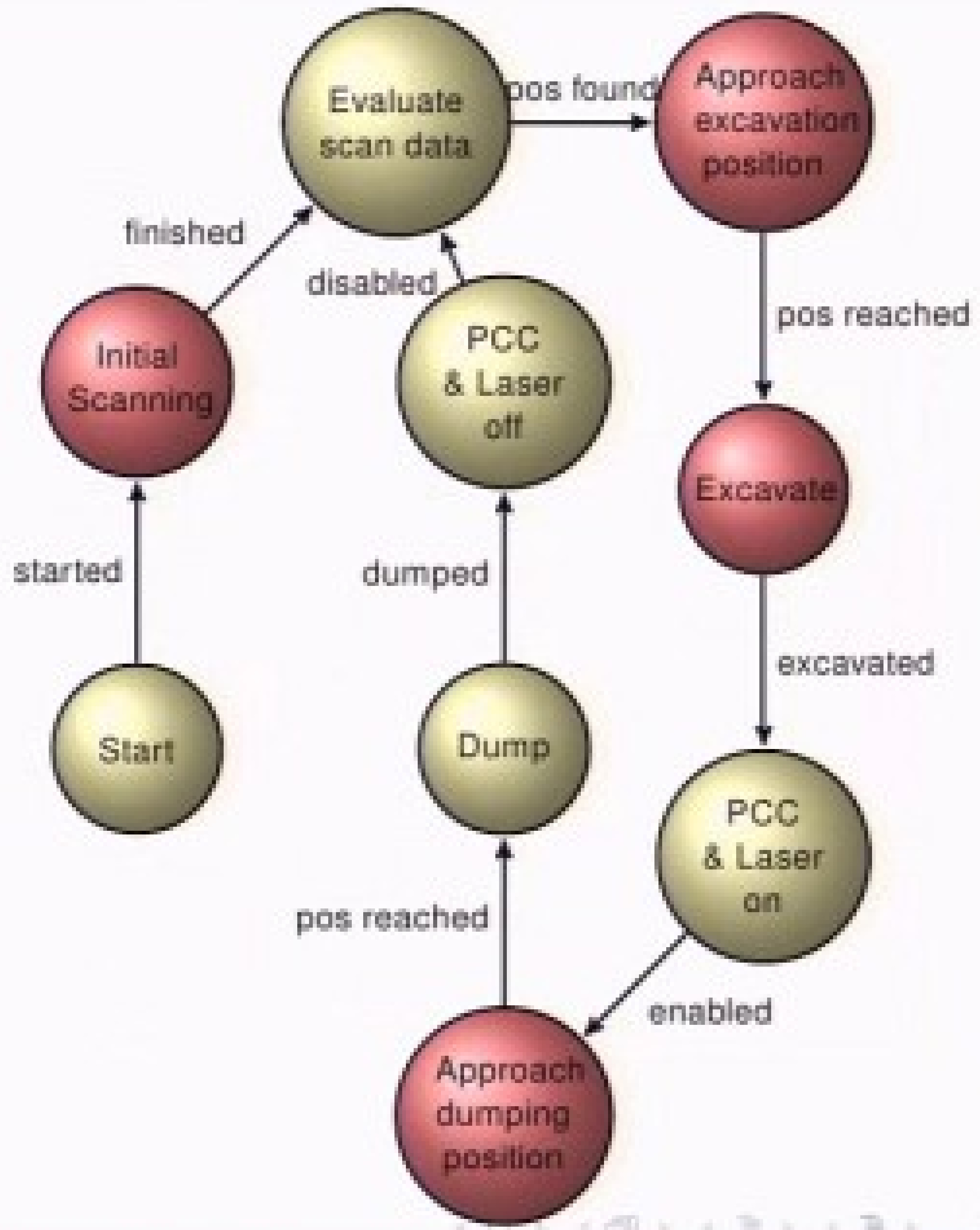


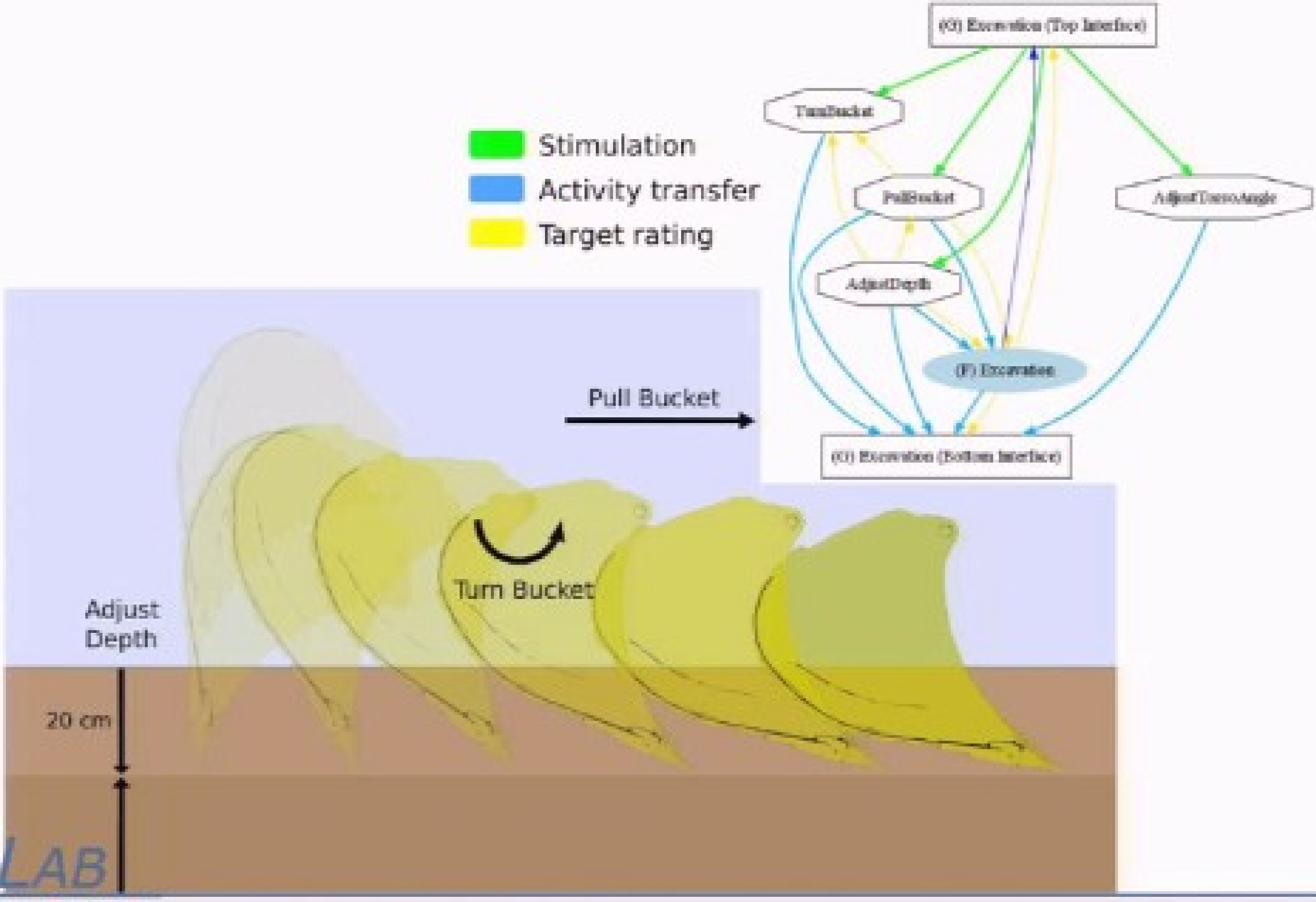
Behaviour-based control cycle

4 main behaviours perform surface shaping

- Initial scanning (surface scan)
- Approach position (excavation or dump position)
- Excavate



Example: excavation group



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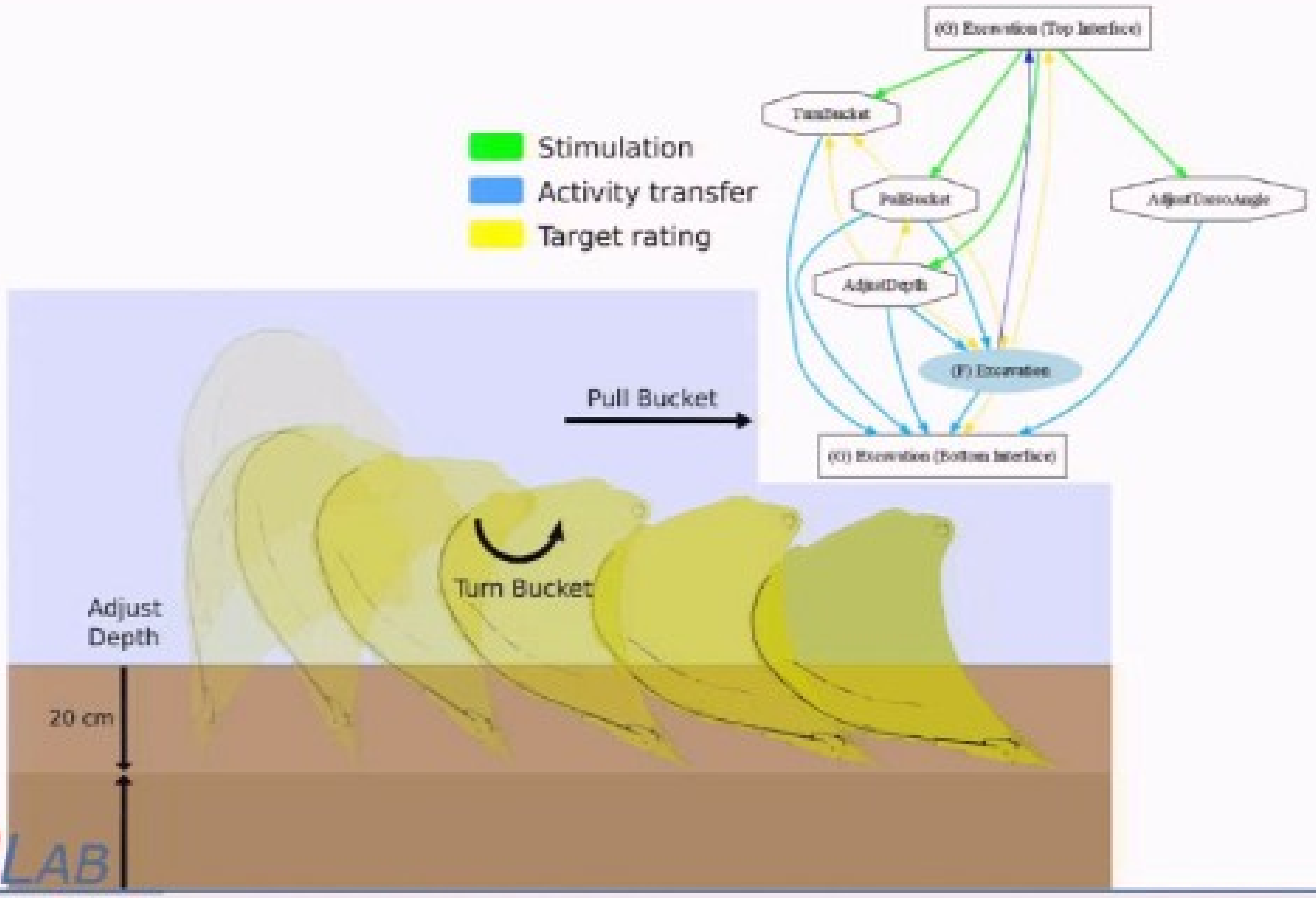


Project results

Simulation

1. Test environment including physics
2. Excavation of soil particles is possible

Real excavator

1. Arm joints, outriggers, shield and drive are controllable
2. Direct and inverse kinematics implemented (drive & boom)
3. Running of teached-in trajectories
4. Behaviour-based control produces suitable trajectories

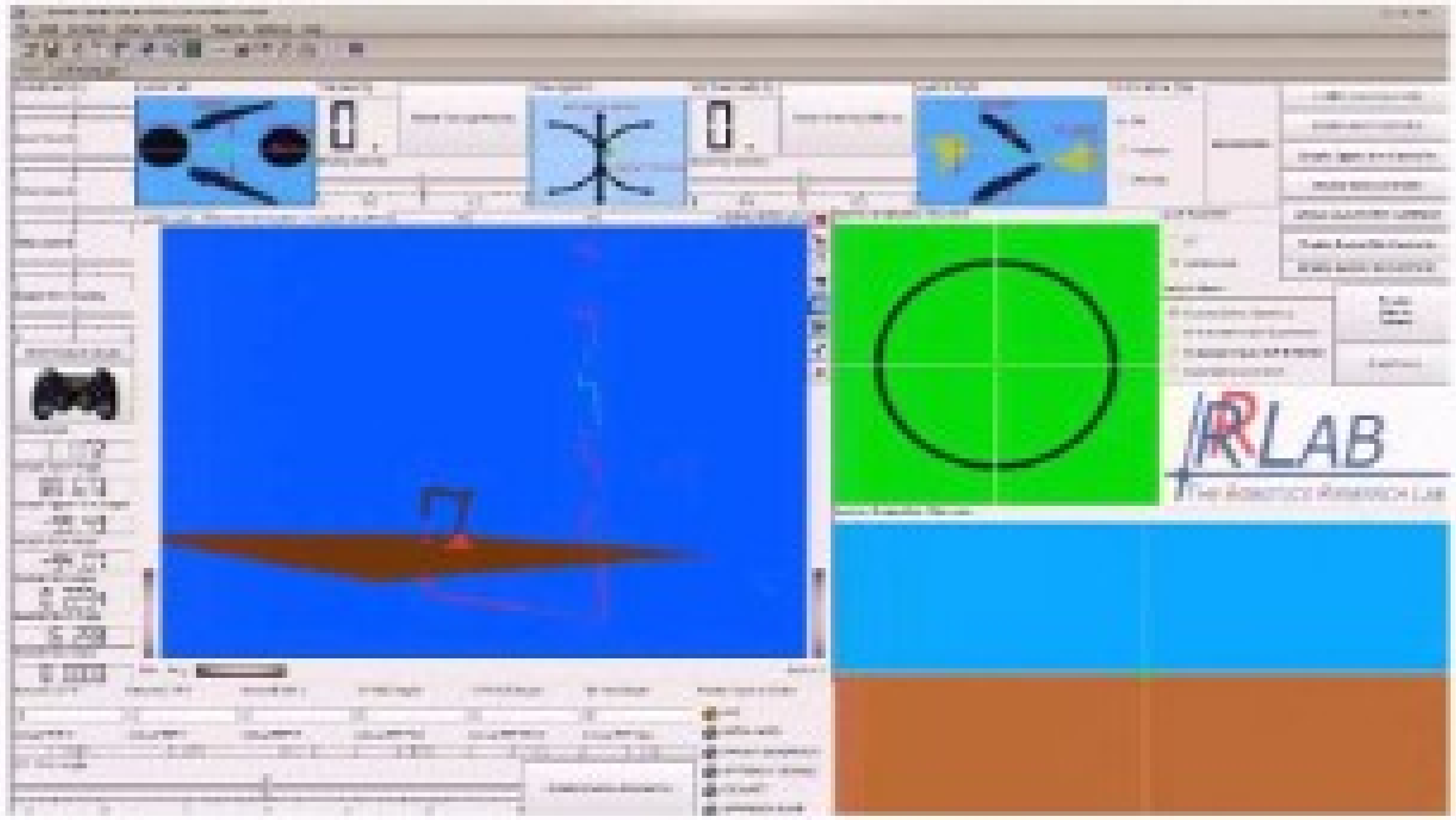
Implicit results

Multiple remote control tools

- Graphical user interface
- Electrical joystick

Different control approaches

- Direct kinematic
- Inverse kinematic



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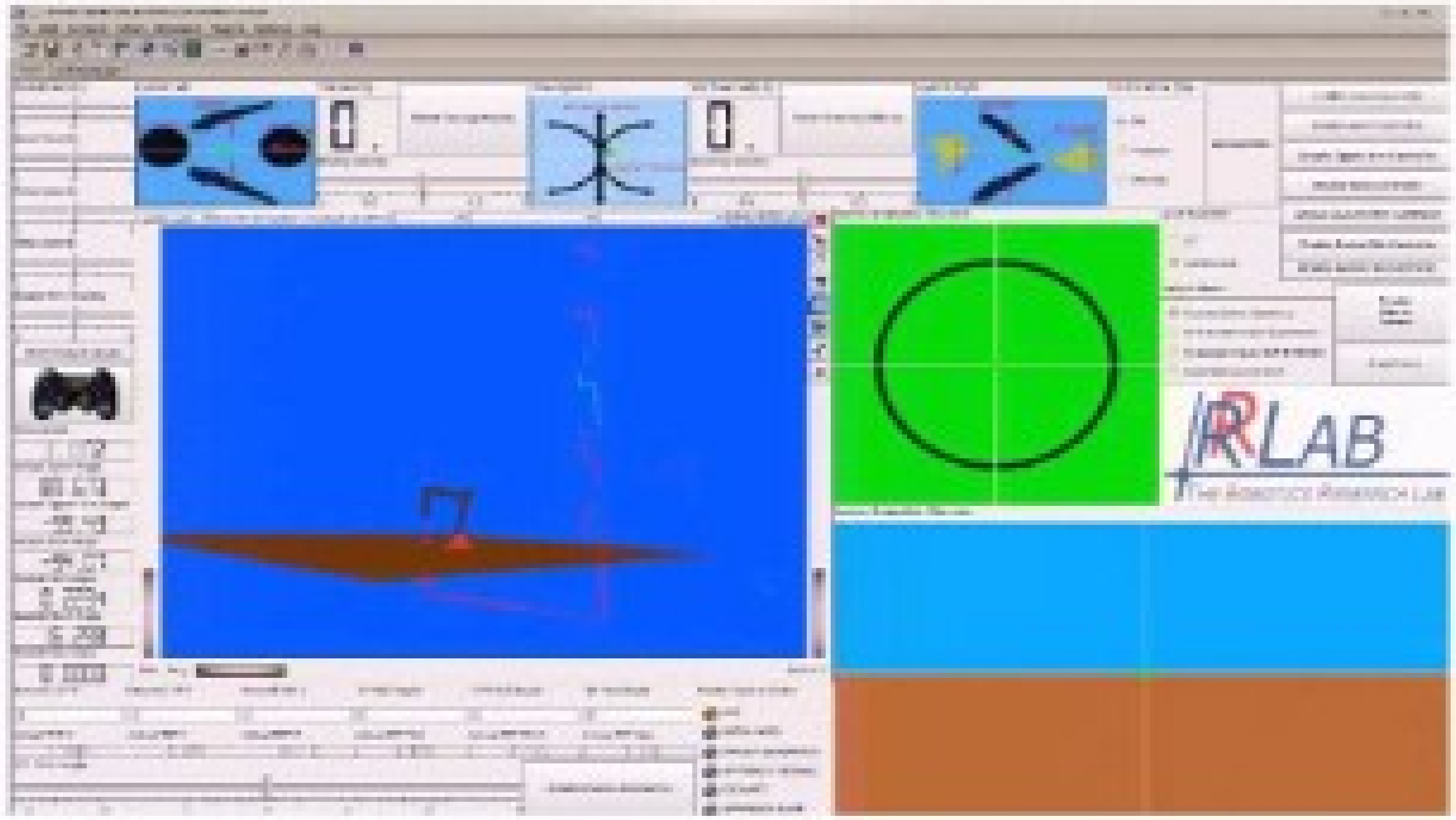
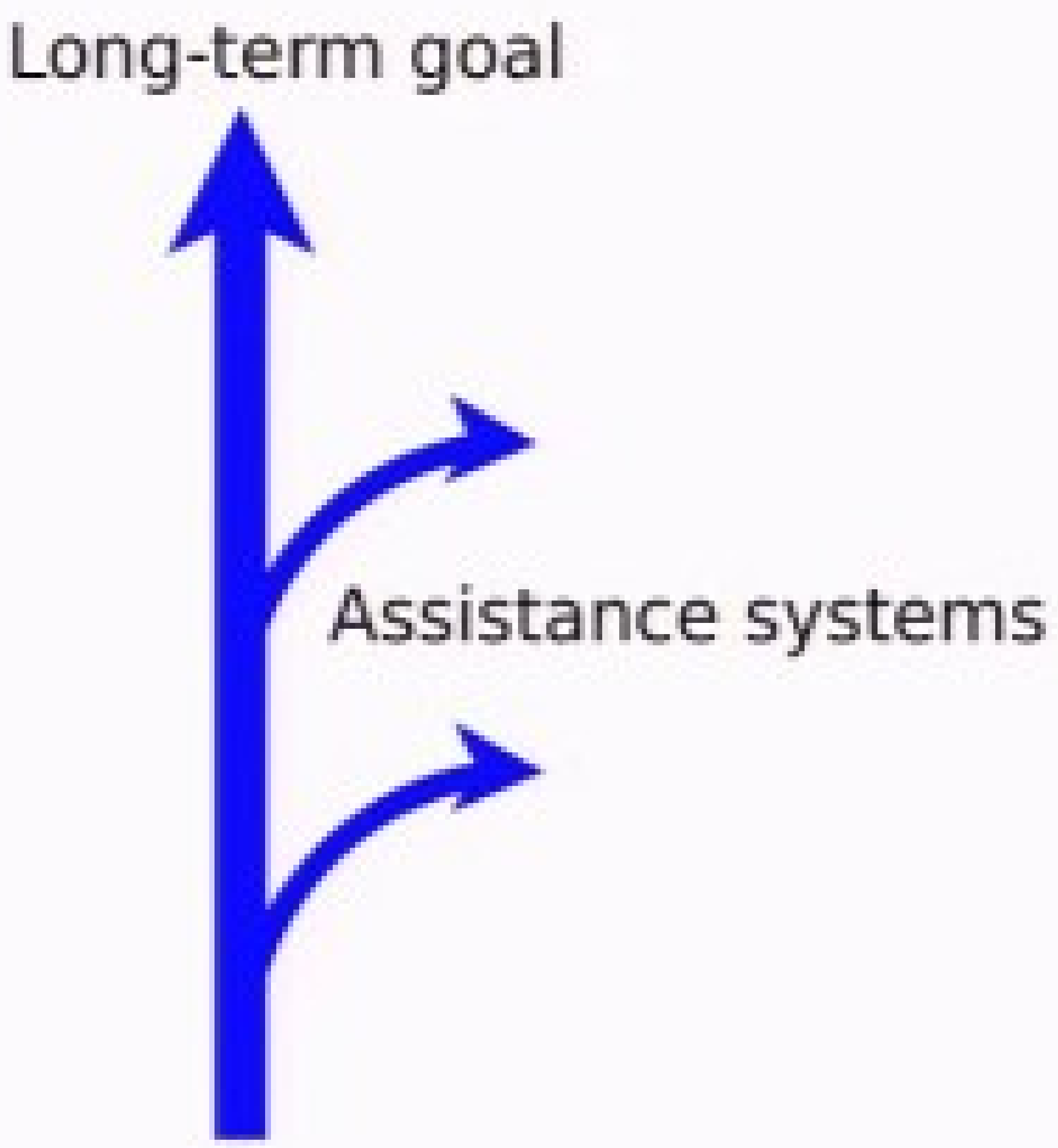


Near-term spin-off results

Assistance systems

- Display presenting the internal and external status of the excavator inside the cabin
- Intelligent alarm mechanism
  - Hitting objects
  - Self damaging
  - High system load
- Restrict operation space
- Teach in trajectories

Roadmap



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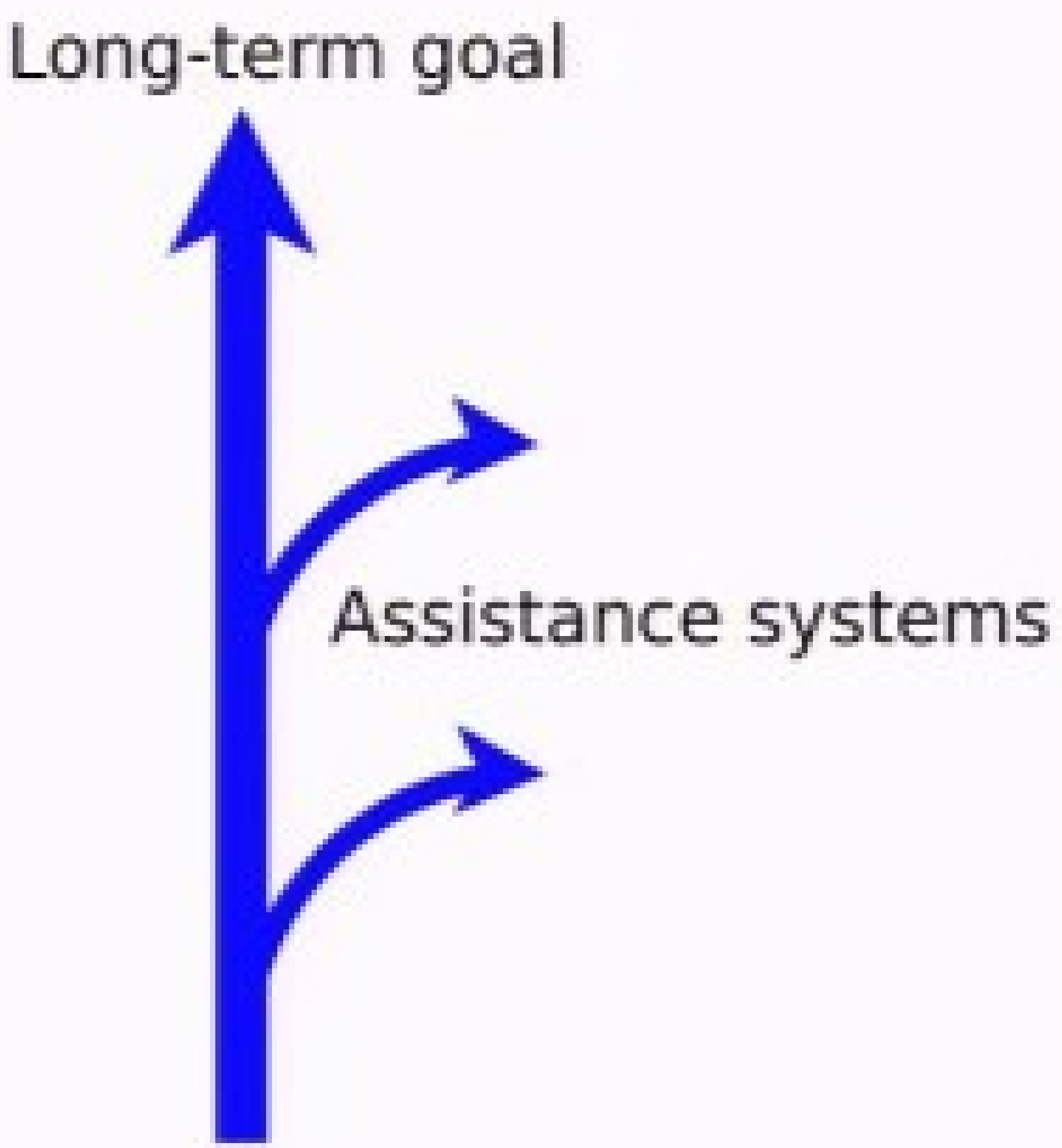


Extension points for the future

- More complex central planner
- Improve environment (change) detection
- Security aspects — avoid dangerous poses
- Stowing/moving on the construction site

Thanks for Your Attention.

Any questions?

RAVON

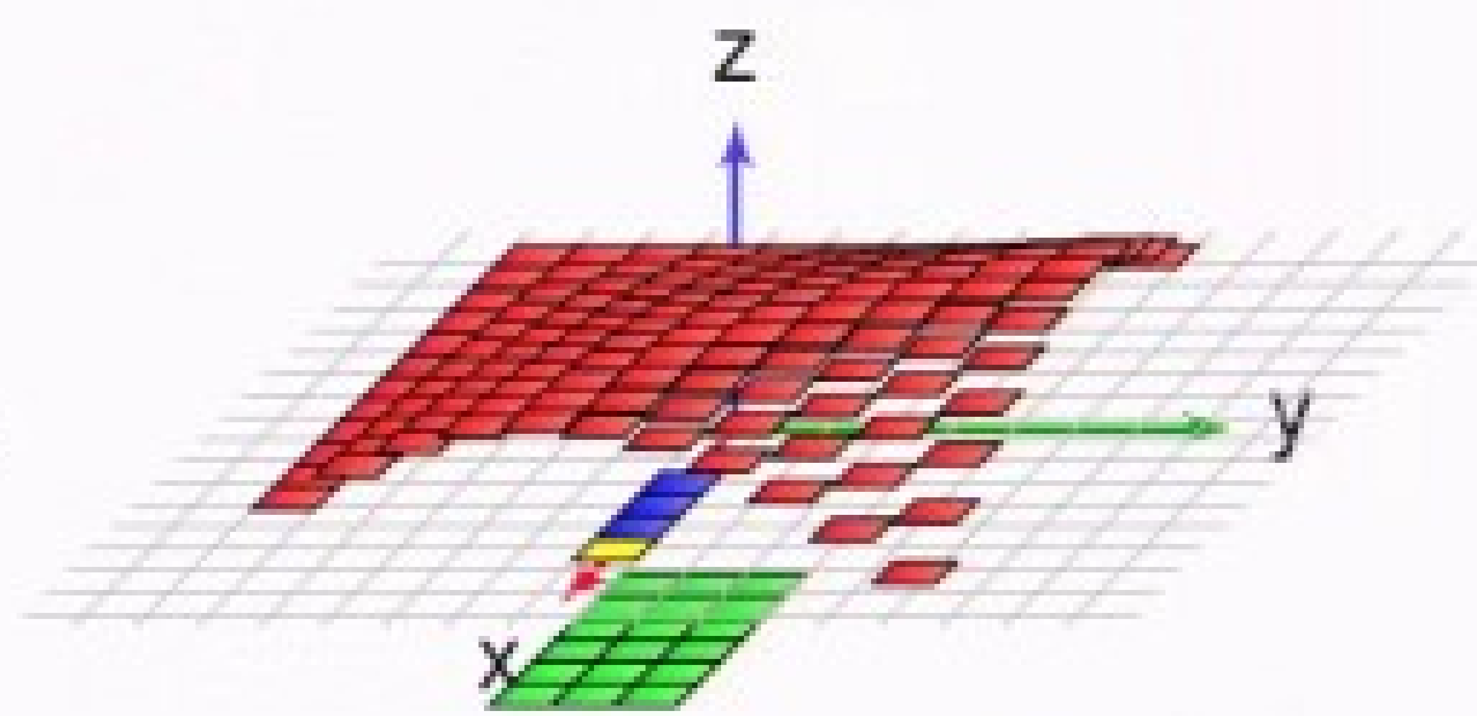
RAVON

Possible excavation positions

- Red: Actual scanned surface (laser distance data)
- Green: Desired surface (generated or constructed surface)
- Blue/yellow: Chosen excavation positions

Laser point cloud

⇒



2D search grid

⇓

`Cell evaluation function`

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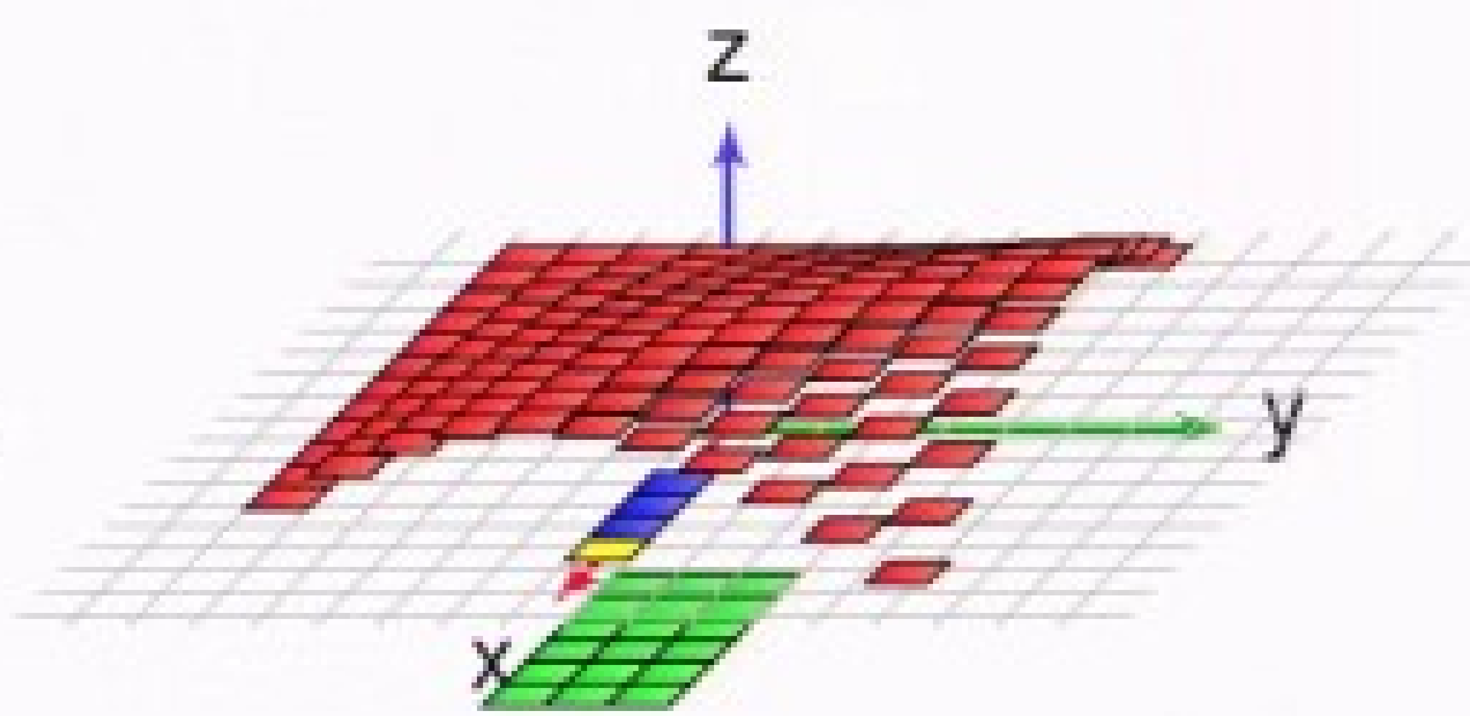


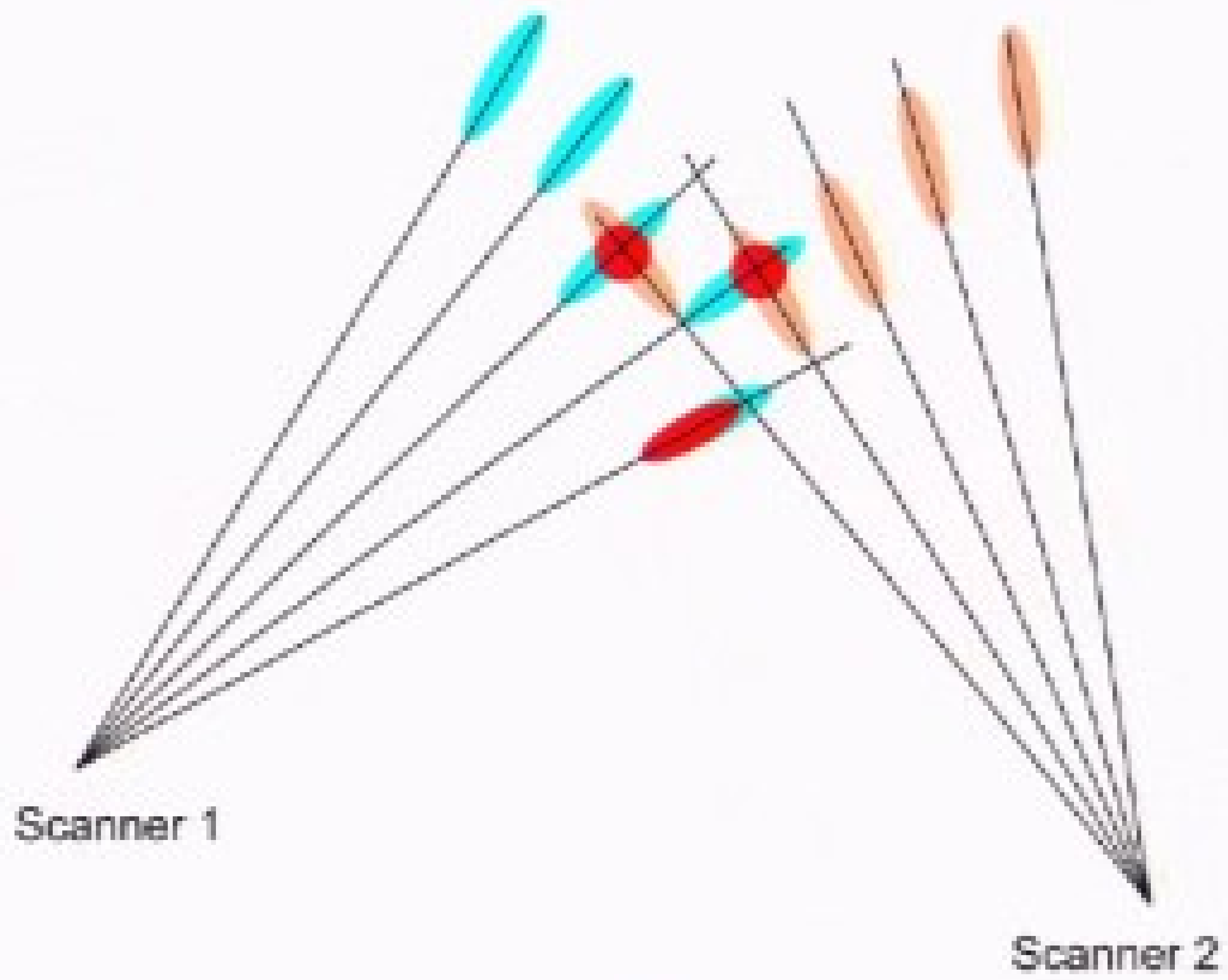
2D search grid

⇓

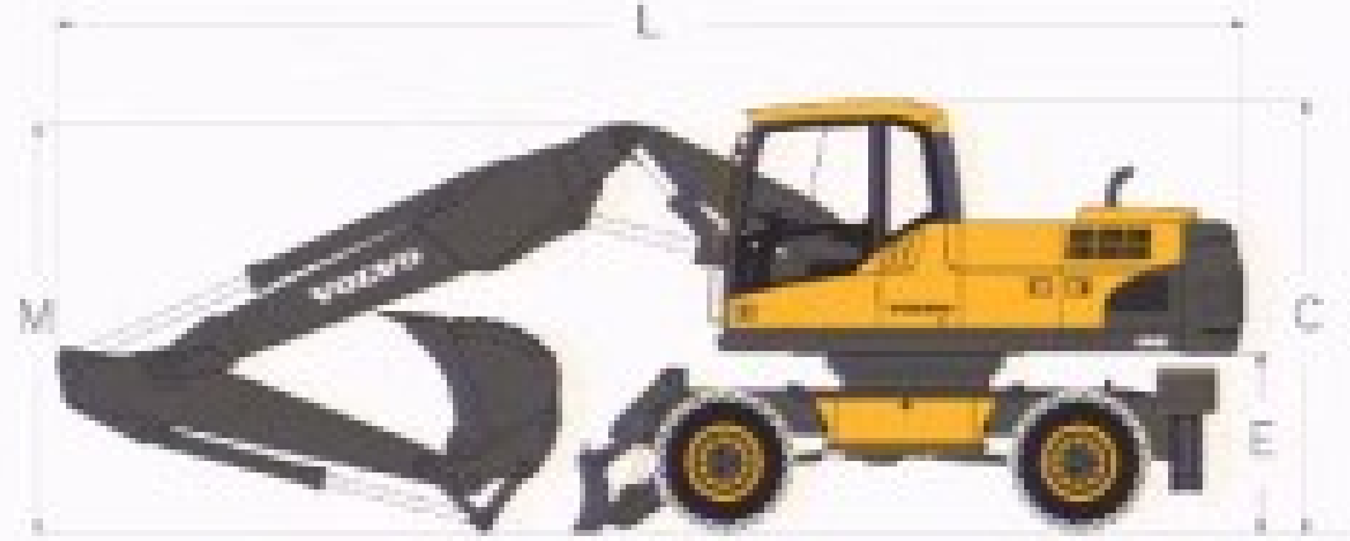
Cell evaluation function

Strategy for handling dynamic surroundings

- Constant movement of sensors to cover wide area
- Use multiple scanners and combine data for higher accuracy:



T.H.O.R. (Terraforming Heavy Outdoor Robot)



Volvo EW/180B

M	2.92 m
L	8.72 m
C	3.17 m
E	1.29 m

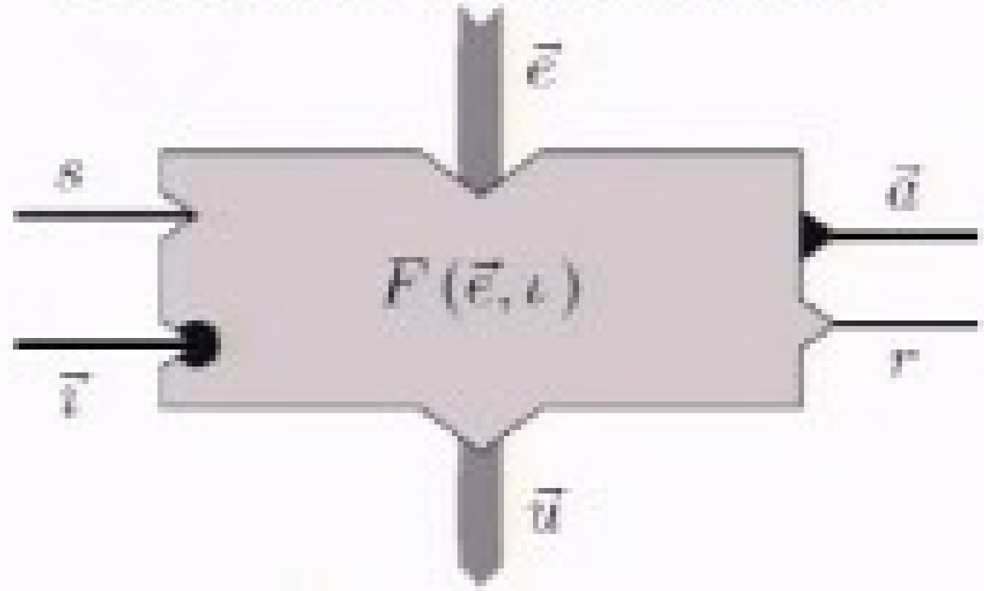
- Mass: 18t
- Lifting force $\approx$ 100kN

The robotics research lab

- Department of computer science at the University of Kaiserslautern
- Head: Professor Dr. Karsten Berns
- 20 PhD students
- Indoor and outdoor robot projects

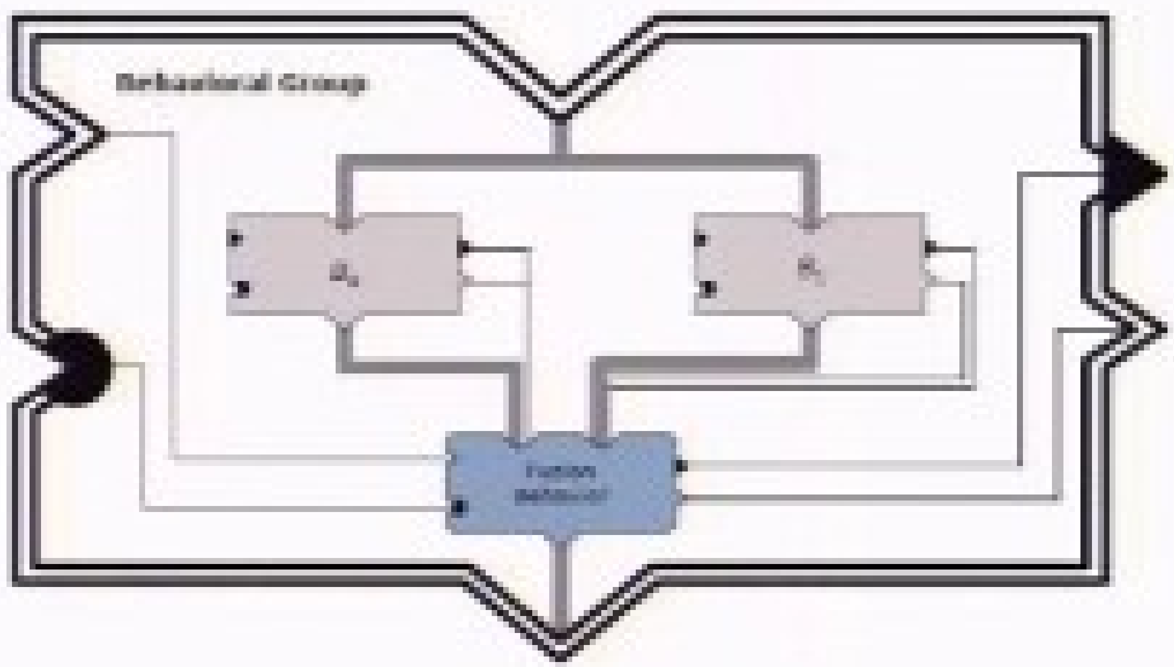
Behaviour-based control structure iB2C [Proetzsch09]

Behaviour module



- stimulation s
- inhibition $\vec{i}$
- activity $\vec{a}$
- target rating r
- input vector $\vec{e}$
- output vector $\vec{u}$

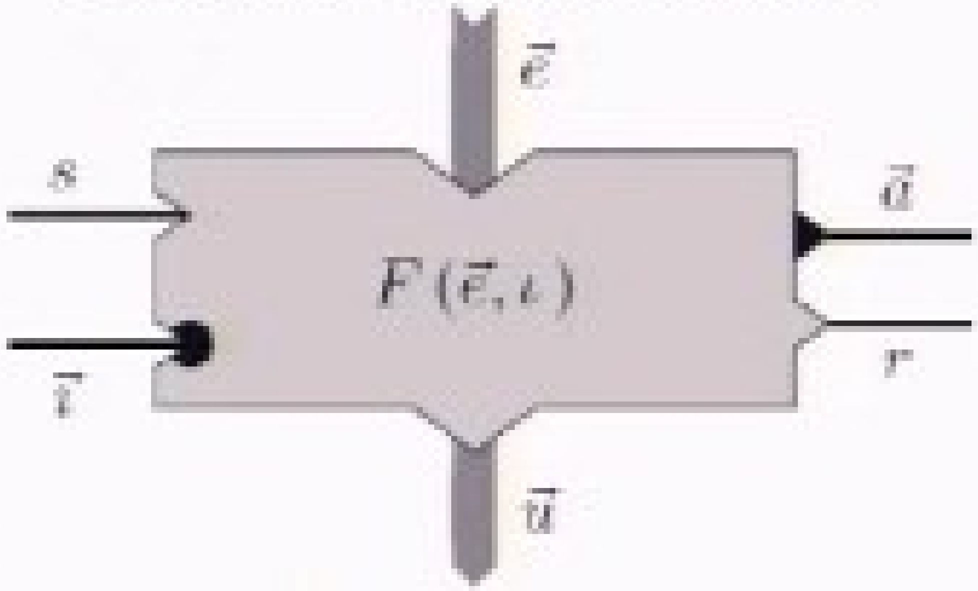
Behaviour Networks Fusion module



- Maximum fusion
- Weighted fusion
- ...

Behaviour-based control structure iB2C [Proetzsch09]

Behaviour module



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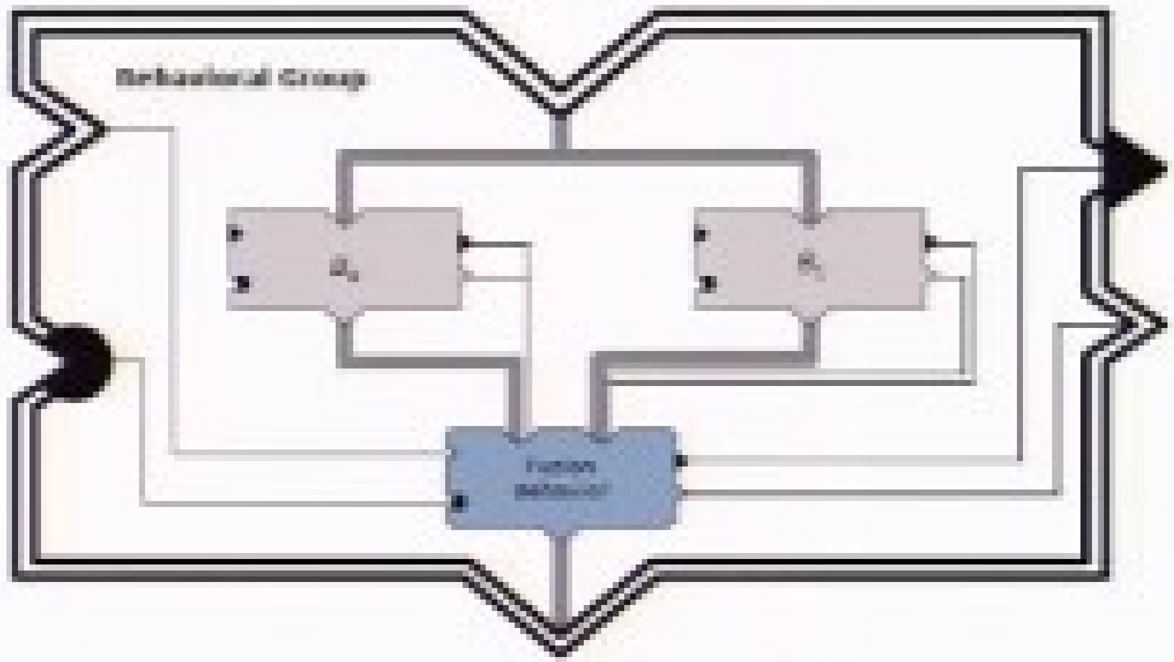

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