Summary and Example in Application

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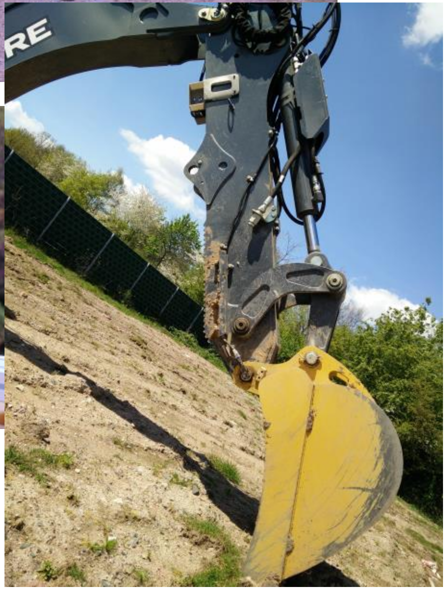
Contents:

Backhoe Loader Platform

- Sensor system
  - Angle encoder (CAN)
  - Laser scanner (rotating)
  - Bucket (ToF)-camera
  - GPS-System
- Control system
  - Individual flow-controlled hydraulic cylinders (already standard)
  - Electronic joysticks
  - Control PC



Digging a Trench on Real Machine

The Mechanical System: DH-Parameters

- Describe kinematics by Denavit-Hartenberg
- One coordinate system per joint
- Main segments moved by hydraulic cylinders
  - positioned parallel to segments.
- Distinction is necessary to give a relation between the deflection of the hydraulic cylinders and the main angle configuration
  - Main Segment Chain
  - Actuator Chain
- Both chains are nearly independent
  - Calculate pose of TCP as they are parallel

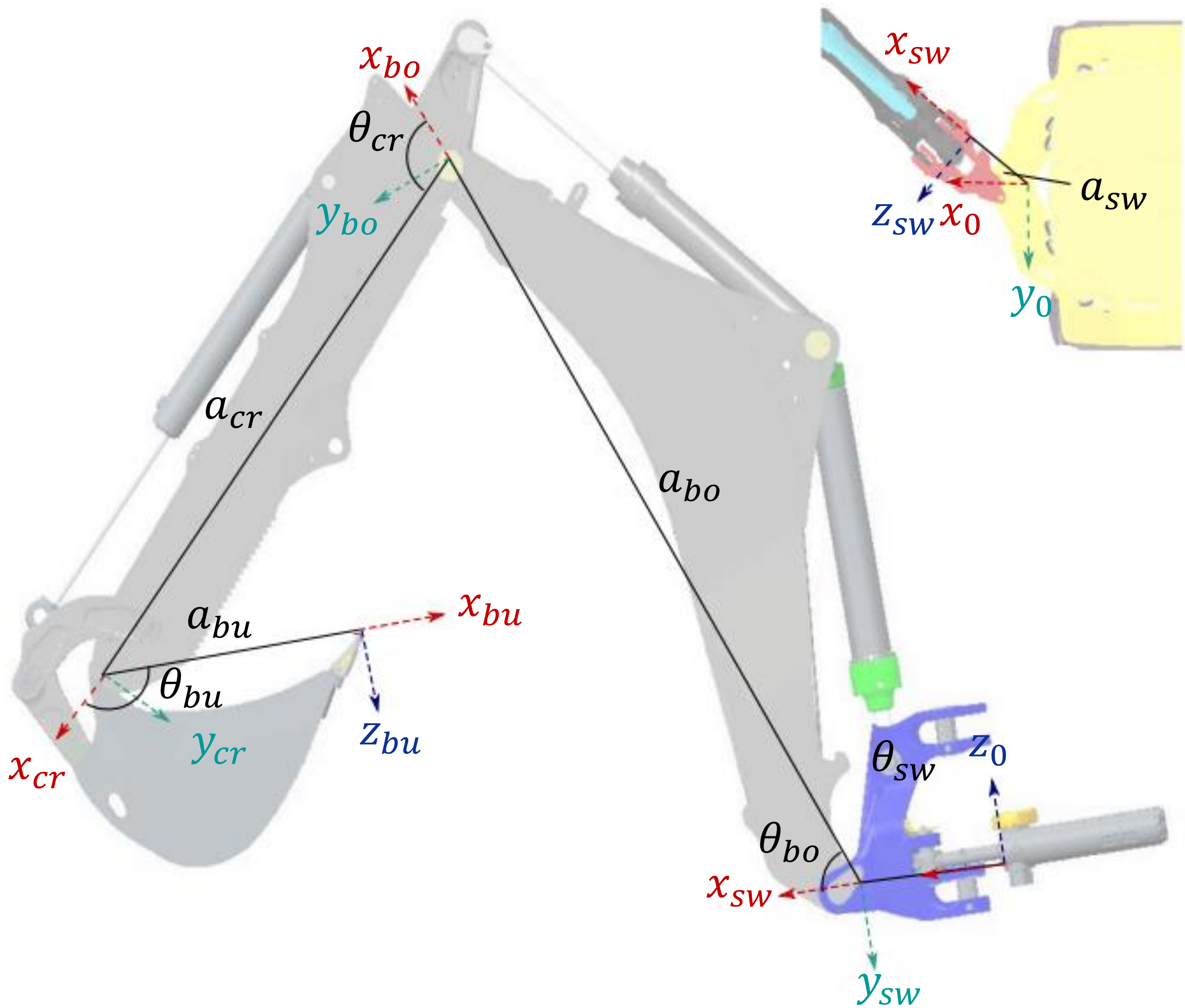
D-H-Parameters: Main Chain Segment

- Backhoe Main D-H-Parameters:

	$\boldsymbol{\theta}$	$\boldsymbol{d}$	$\boldsymbol{a}\ (\boldsymbol{mm})$	$\boldsymbol{\alpha}$
J_0				
J_{sw}	θ_{sw}	0	a_{sw}=465	90°
J_{bo}	θ_{bo}	0	a_{bo}=2829.86	0
J_{cr}	θ_{cr}	0	a_{cr}=2144.85	0
J_{bu}	θ_{bu}	0	a_{bu}=945.065	90°

- $\theta_{sw}, \theta_{bo}, \theta_{cr}$, and θ_{bu} : Angles of backhoe arm
- a_{sw}, a_{bo}, a_{cr}, and a_{bu} : Segment lengths

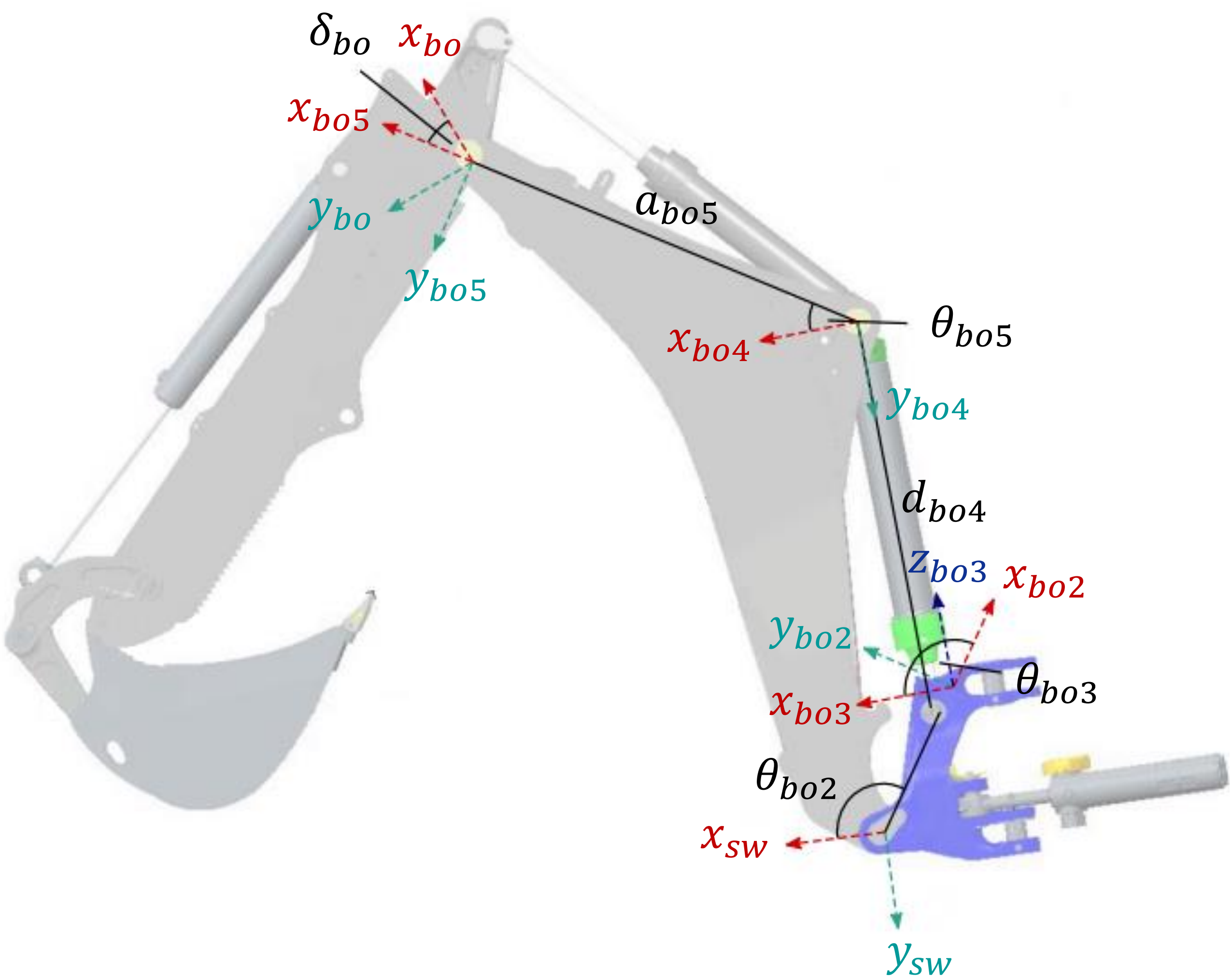
Backhoe Main D-H-Parameters



Actuator Chain

- Describes:
  - Deflection of the hydraulic cylinders
  - Angular displacement of revolute joints surrounding them
- A set of parameters for every available hydraulic cylinder:
  - Boom parameters
  - Crowd parameters
  - Bucket parameters
- Gives a relation between the deflection of a hydraulic cylinder and the position of the appropriated backhoe part

Boom Hydraulic D-H-Parameters

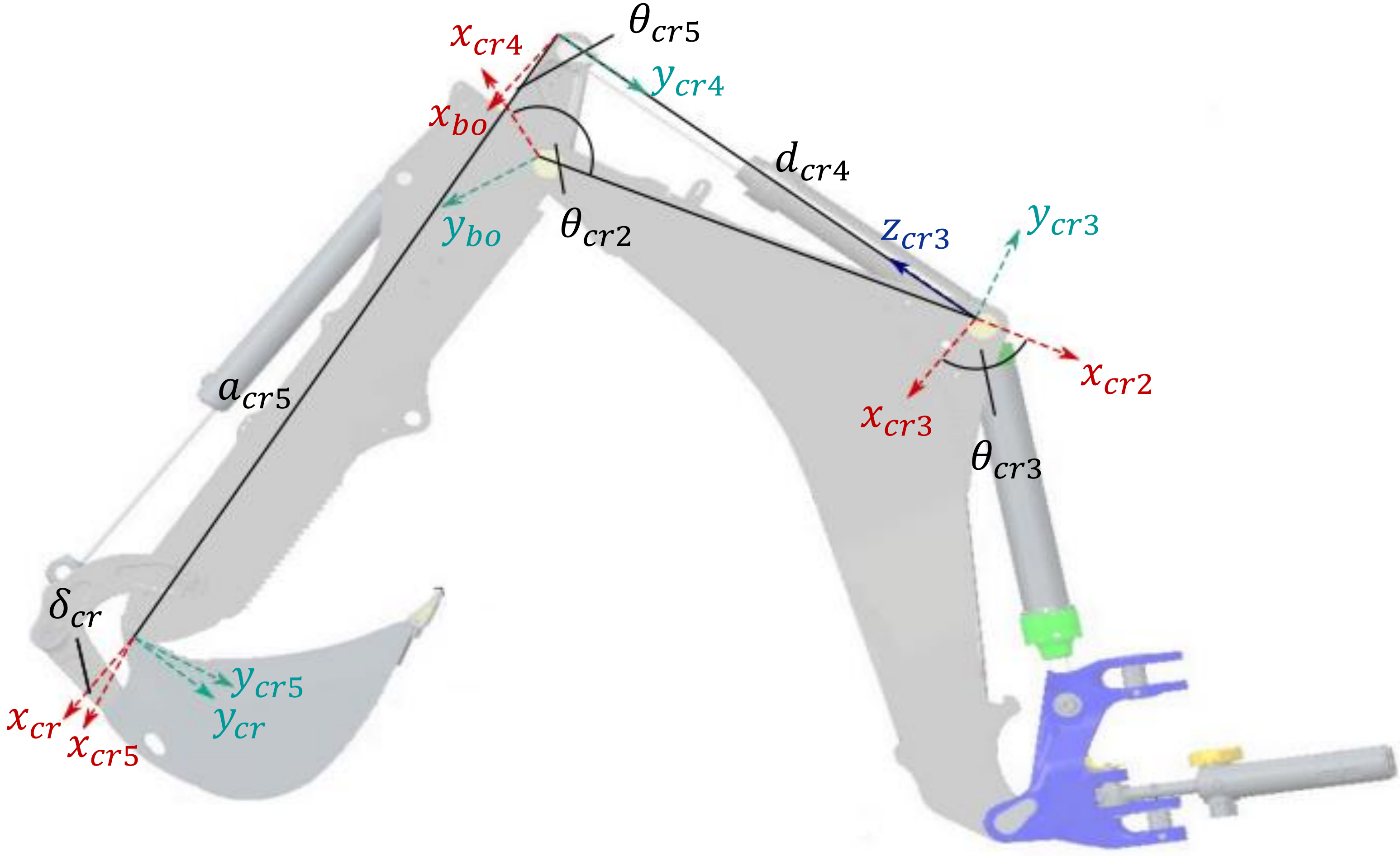


Actuator Chain

- D-H-parameter of boom hydraulics

Joint	$\boldsymbol{\theta}$	$\boldsymbol{d}$ (mm)	$\boldsymbol{a}$ $(\boldsymbol{mm})$	$\boldsymbol{\alpha}$
J_{sw}				
J_{bo2}	$\theta_{\mathrm{bo2}}=-121.422^{\circ}$	0	a_{bo}=472.283	0
J_{bo3}	θ_{bo3}	0	0	90°
J_{bo4}	0	d_{bo4}=1372.5+(0;800)	a_{cr}=2144.85	-90°
J_{bo5}	θ_{bo5}	0	$a_{bo5} = 1478.3$	0
J_{bo}	$\delta_{\mathrm{bo}}=-35.698^{\circ}$	0	0	0

Crowd Hydraulic D-H-Parameters

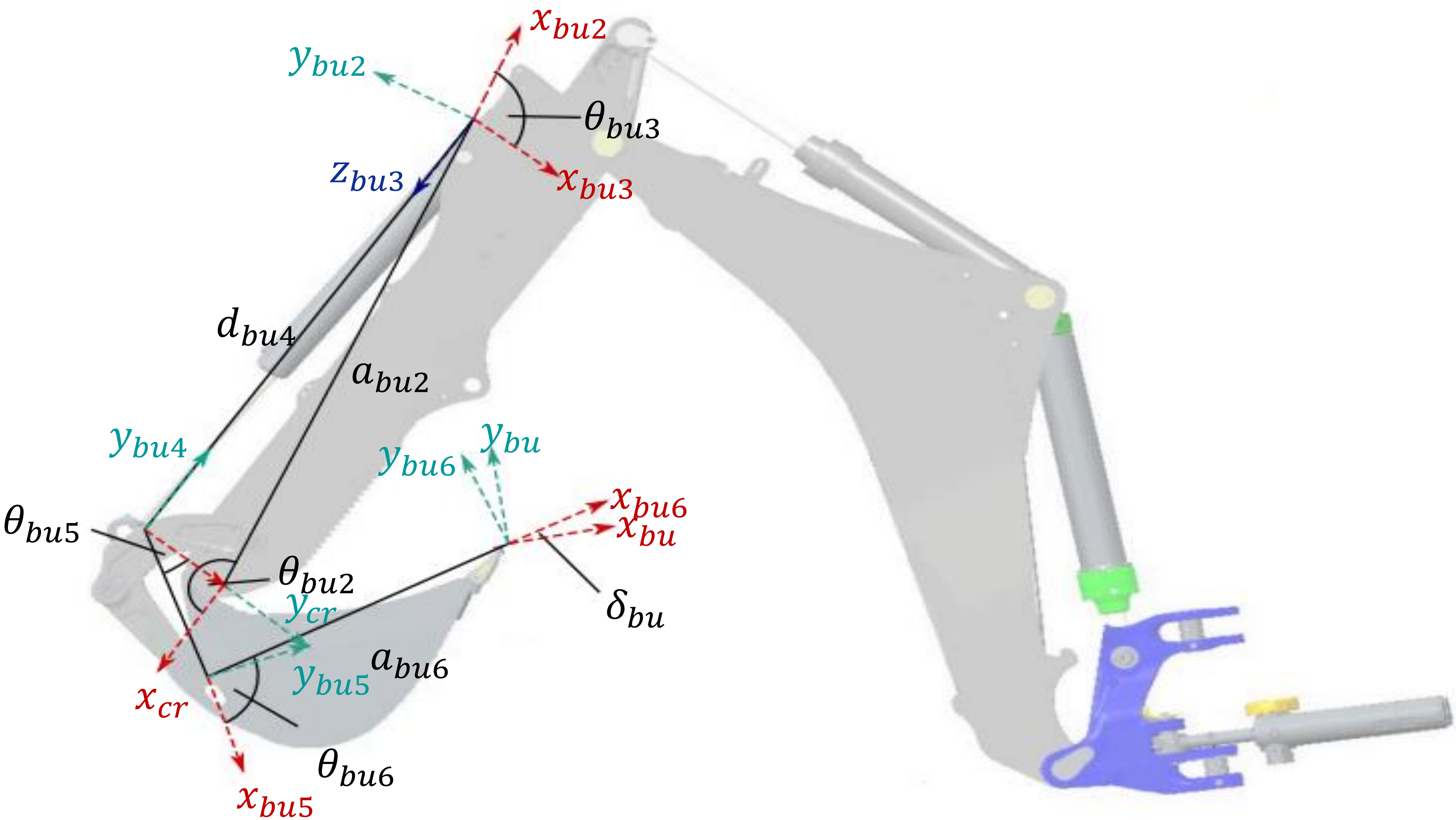


Actuator Chain

- D-H-parameter of crowd hydraulics

Joint	$\boldsymbol{\theta}$	$\boldsymbol{d}$ (mm)	$\boldsymbol{a}$ $(\boldsymbol{mm})$	$\boldsymbol{\alpha}$
J_{bo}				
J_{cr2}	$\theta_{\mathrm{cr2}}=-144.302^{\circ}$	0	$a_{\mathrm{cr2}}=1478.3$	0
J_{cr3}	θ_{cr3}	0	0	90°
J_{cr4}	0	$d_{cr4}=1122.7+(0;700)$	0	-90°
J_{cr5}	θ_{cr5}	0	$a_{\mathrm{cr5}} = 2530.25$	0
J_{cr}	$\delta_{\mathrm{cr}}=-4.3423^{\circ}$	0	0	0

Bucket Hydraulic D-H-Parameters

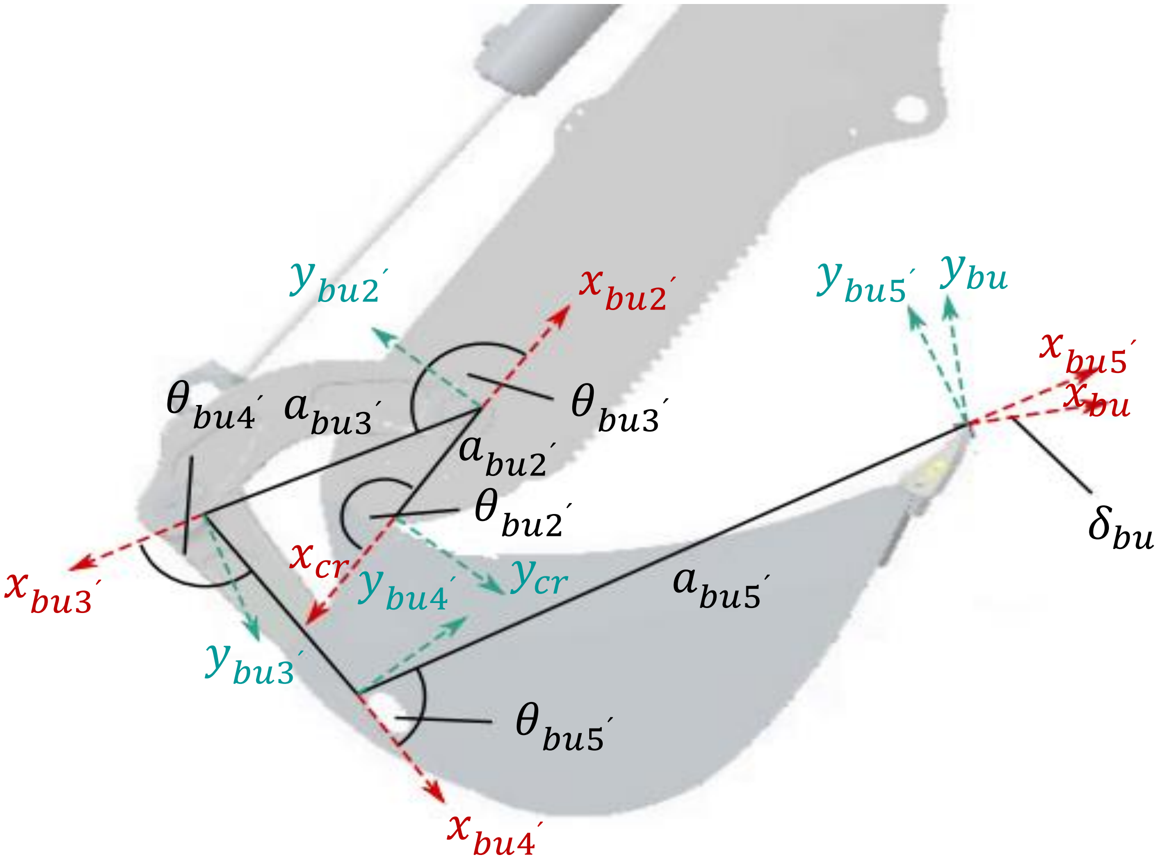


Actuator Chain

- D-H-parameter for bucket hydraulics

Joint	$\boldsymbol{\theta}$	$\boldsymbol{d}$ (mm)	$\boldsymbol{a}$ $(\boldsymbol{mm})$	$\boldsymbol{\alpha}$
J_{cr}				
J_{bu2}	$\theta_{\mathrm{bu2}}=-169.791^{\circ}$	0	$a_{\mathrm{bu2}}=1864.53$	0
J_{bu3}	θ_{bu3}	0	0	90°
J_{bu4}	0	$d_{bu4}=1145.5+(0;800)$	0	-90°
J_{bu5}	θ_{bu5}	0	$a_{\mathrm{bu5}}=476.56$	0
J_{bu6}	θ_{bu6}	0	$a_{\mathrm{bu6}}=1090.59$	0
J_{bu}	$\delta_{\mathrm{bu}}=-22.1181^{\circ}$	0	0	0

Bucket Linkage D-H-Parameters



Actuator Chain

- D-H-parameter for the bucket gear

Joint	$\boldsymbol{\theta}$	$\boldsymbol{d}$ (mm)	$\boldsymbol{a}$ $(\boldsymbol{mm})$	$\boldsymbol{\alpha}$
J_{cr}				
$J_{bu2'}$	$\theta_{bu2'} = -178.478^{\circ}$	0	$a_{bu2'} = 237.472$	0
$J_{bu3'}$	$\theta_{bu3'}$	0	$a_{bu3'} = 480$	0
$J_{bu4'}$	$\theta_{bu4'}$	0	$a_{bu4'} = 380$	0
$J_{bu5'}$	$\theta_{bu5'}$	0	$a_{bu5'} = 476.56$	0
J_{bu}	$\delta_{bu'} = -22.1181^{\circ}$	0	0	0

Forward Kinematics

- Pose of the TCP: $P_{bu} = (x, y, z, \phi, \theta, \psi)$
- $(x, y, z)^T$: Translation to this point from the base coordinate system.
- (ϕ, θ, ψ): Orientation of the TCP
  - roll angle ϕ: rotation around the x-axis,
  - yaw angle θ: rotation around the y-axis
  - pitch angle ψ: rotation around the z-axis
- ${}^{0}_{sw}A$: Transition between the base coordinate system (x_0, y_0, z_0) and pose of the swing coordinate system (x_{sw}, y_{sw}, z_{sw})

$$
{}^{0}_{sw}A = \begin{bmatrix} \cos(\theta_{sw}) & 0 & -\sin(\theta_{sw}) & a_{sw} \cdot \cos(\theta_{sw}) \\ \sin(\theta_{sw}) & 0 & \cos(\theta_{sw}) & a_{sw} \cdot \sin(\theta_{sw}) \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

Forward Kinematics

- Change the basis from swing to boom coordinate system:

$$^{sw}_{bo}A = R_{zsw}(\theta_{bo}) \cdot T_{xbo}(a_{bo})$$

$$= \begin{bmatrix} \cos(\theta_{bo}) & -\sin(\theta_{bo}) & 0 & a_{bo} \cdot \cos(\theta_{bo}) \\ \sin(\theta_{bo}) & \cos(\theta_{bo}) & 0 & a_{bo} \cdot \sin(\theta_{bo}) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

- Change the basis from boom to crowd coordinate system:

$$^{bo}_{cr}A = R_{zbo}(\theta_{cr}) \cdot T_{xcr}(a_{cr})$$

$$= \begin{bmatrix} \cos(\theta_{cr}) & -\sin(\theta_{cr}) & 0 & a_{cr} \cdot \cos(\theta_{cr}) \\ \sin(\theta_{cr}) & \cos(\theta_{cr}) & 0 & a_{cr} \cdot \sin(\theta_{cr}) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Forward Kinematics

- Change the basis from crowd to bucket coordinate system:

$$ {}^{cr}_{bu}A = R_{z3}(\theta_{bu}) \cdot T_{xTCP}(a_{bu}) \cdot R_{xTCP}(90^{\circ}) $$

$$ = \begin{bmatrix} \cos(\theta_{bu}) & 0 & -\sin(\theta_{bu}) & a_{bu} \cdot \cos(\theta_{bu}) \\ \sin(\theta_{bu}) & 0 & \cos(\theta_{bu}) & a_{bu} \cdot \sin(\theta_{bu}) \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Forward Kinematics

- Multiplication of all these transformation matrices

$$ {}^{0}_{bu}A = {}^{0}_{sw}A \cdot {}^{sw}_{bo}A \cdot {}^{bo}_{cr}A \cdot {}^{cr}_{bu}A $$

$$ = \begin{bmatrix} C_{bo\cdot cr\cdot bu}.C_{sw} & -S_{sw} & S_{bo\cdot cr\cdot bu}.C_{sw} & \begin{matrix} C_{sw}\cdot(a_{sw}+a_{cr} \\ \cdot C_{bo\cdot cr}+a_{bo}C_{bo}) \\ a_{bu}.C_{bo\cdot cr\cdot bu} \end{matrix} \\ C_{bo\cdot cr\cdot bu}.S_{sw} & C_{sw} & S_{bo\cdot cr\cdot bu}.S_{sw} & \begin{matrix} S_{sw}\cdot(a_{sw}+a_{cr} \\ \cdot C_{bo\cdot cr}+a_{bo}C_{bo}) \\ a_{bu}.C_{bo\cdot cr\cdot bu} \end{matrix} \\ -S_{bo\cdot cr\cdot bu} & 0 & S_{bo\cdot cr\cdot bu} & \begin{matrix} -a_{cr}\cdot S_{bo\cdot cr} - a_{bo}\cdot S_{bo} \\ -a_{bu}\cdot S_{bo\cdot cr\cdot bu} \end{matrix} \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Notation:

$\sin(\theta_{bo}+\theta_{cr}+\theta_{bu}) = S_{bo\cdot cr.bu}$ and $\cos(\theta_{bo}+\theta_{cr}+\theta_{bu}) = C_{bo\cdot cr.bu}$

Forward Kinematics

- Direct transformation from the base coordinate system to the TCP:

$${}^{0}_{bu}T =$$

$$= \begin{bmatrix} C\theta \cdot C\psi & C\psi \cdot S\phi \cdot S\theta - C\phi \cdot S\psi & S\phi \cdot S\psi + C\phi \cdot C\phi \cdot S\theta & x \\ C\theta \cdot S\psi & C\psi \cdot C\phi + S\phi \cdot S\theta \cdot S\psi & C\phi \cdot S\theta \cdot S\psi - C\psi \cdot S\phi & y \\ -S\theta & C\theta \cdot S\phi & C\theta \cdot C\phi & z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

- There is no joint to bucket $\Longrightarrow \psi$=0

$${}^{0}_{bu}T = \begin{bmatrix} C\theta \cdot C\psi & -S\psi & C\phi \cdot S\theta & x \\ C\theta \cdot S\psi & C\psi & S\theta \cdot S\psi & y \\ -S\theta & 0 & C\theta & z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

- Remember: $\sin(0) = 0$ and, $\cos(0) = 1$

Forward Kinematics

- ${}_{bu}^{0}T = {}_{bu}^{0}A$

$$\begin{bmatrix} x \\ y \\ z \\ \phi \\ \theta \\ \varphi \end{bmatrix} = \begin{bmatrix} C_{sw} + (a_{sw} + a_{cr} \cdot C_{bo \cdot cr} + a_{bu} \cdot C_{bo \cdot cr \cdot bu}) \\ S_{sw} + (a_{sw} + a_{cr} \cdot C_{bo \cdot cr} + a_{bu} \cdot C_{bo \cdot cr \cdot bu}) \\ -a_{cr} S_{bo \cdot cr} - a_{bo} S_{bo} - a_{bo} S_{cr \cdot bu} \\ 0 \\ \theta_{bo} + \theta_{cr} + \theta_{bu} \\ \theta_{sw} \end{bmatrix}$$

Inverse Kinematic

- Gives a solution for the problem that the pose of the bu is given and the main angles of the backhoe are not.
- ${}_{sw}^{0}A^{-1} \cdot {}_{bu}^{0}T = {}_{sw}^{0}A^{-1} \cdot {}_{bu}^{0}A$

$$\begin{bmatrix} C(\psi - \theta_{sw}) \cdot C\theta & -S((\psi - \theta_{sw}) & C(\psi - \theta_{sw}) \cdot S\theta & x \cdot C_{sw} - a_{sw} + y \cdot S_{sw} \\ S\theta & 0 & -C\theta & -z \\ S(\psi - \theta_{sw}) \cdot C\theta & C((\psi - \theta_{sw}) & S(\psi - \theta_{sw}) \cdot S\theta & y \cdot C_{sw} - x \cdot S_{sw} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} C_{bo \cdot cr \cdot bu} & 0 & S_{bo \cdot cr \cdot bu} & a_{cr} \cdot C_{bo \cdot cr} + a_{bo} \cdot C_{bo} + a_{bu} \cdot C_{bo \cdot cr \cdot bu} \\ S_{bo \cdot cr \cdot bu} & 0 & -C_{bo \cdot cr \cdot bu} & a_{cr} \cdot S_{bo \cdot cr} + a_{bo} \cdot S_{bo} + a_{bu} \cdot S_{bo \cdot cr \cdot bu} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Inverse Kinematic

- From forward Kinematic: $\theta_{sw} = \psi$ and $\theta = \theta_{bo} + \theta_{cr} + \theta_{bu}$

$$\begin{bmatrix} C\theta & 0 & S\theta & x \cdot C\psi - a_{sw} + y \cdot S\psi \\ S\theta & 0 & -C\theta & -z \\ 0 & 1 & 0 & y \cdot C\psi - x \cdot S\psi \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} C\theta & 0 & S\theta & a_{cr} \cdot C_{bo \cdot cr} + a_{bo} . C_{bo} + a_{bu} \cdot C\theta \\ S\theta & 0 & -C\theta & a_{cr} \cdot S_{bo \cdot cr} + a_{bo} \cdot S_{bo} + a_{bu} \cdot S\theta \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

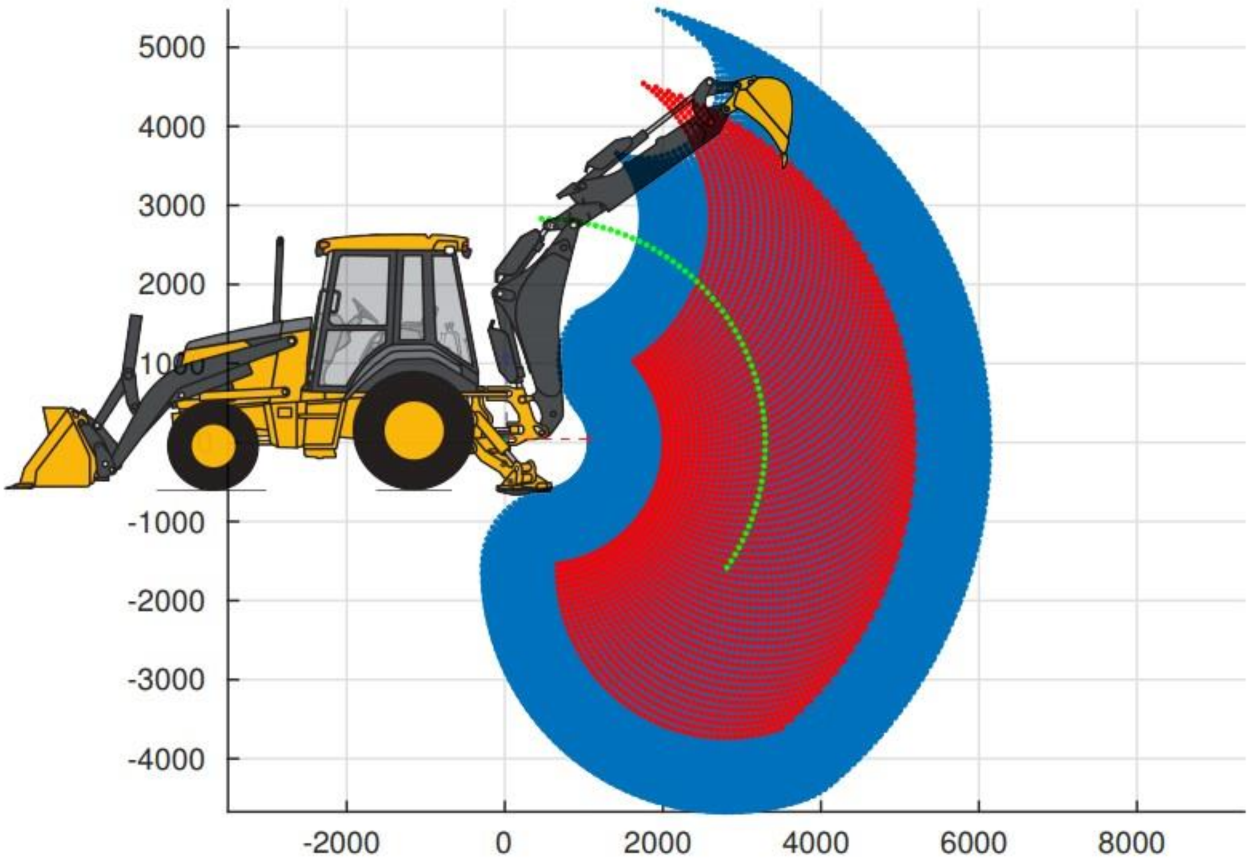
Inverse Kinematic

- $${}^{sw}_{bu}T = \begin{bmatrix} \cos(\theta) & 0 & \sin(\theta) & {}_{sw}x \\ \sin(\theta) & 0 & -\cos(\theta) & {}_{sw}y \\ 0 & 1 & 0 & {}_{sw}z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

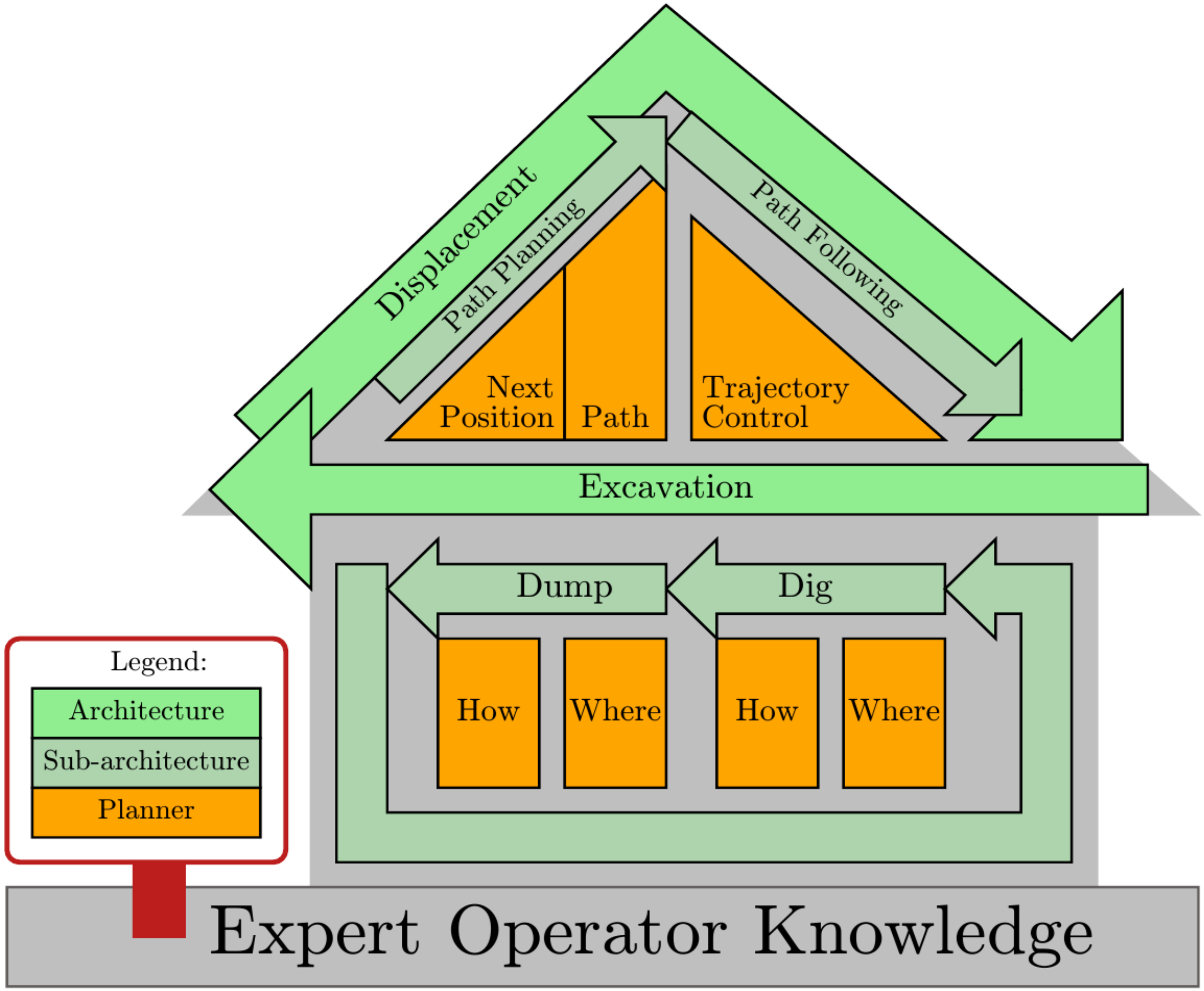
- $$\begin{bmatrix} x \cdot \cos(\psi) - a_{sw} + y \cdot \sin(\psi) \\ -z \\ y \cdot \cos(\psi) - x \cdot \sin(\psi) \end{bmatrix} = \begin{bmatrix} {}_{sw}x \\ {}_{sw}y \\ {}_{sw}z \end{bmatrix} =$$

$$\begin{bmatrix} a_{cr} \cdot C_{bo \cdot cr} + a_{bo} \cdot C_{bo} + a_{bu} \cdot \cos(\theta) \\ a_{cr} \cdot S_{bo \cdot cr} + a_{bo} \cdot S_{bo} + a_{bu} \cdot \cos(\theta) \\ 0 \end{bmatrix}$$

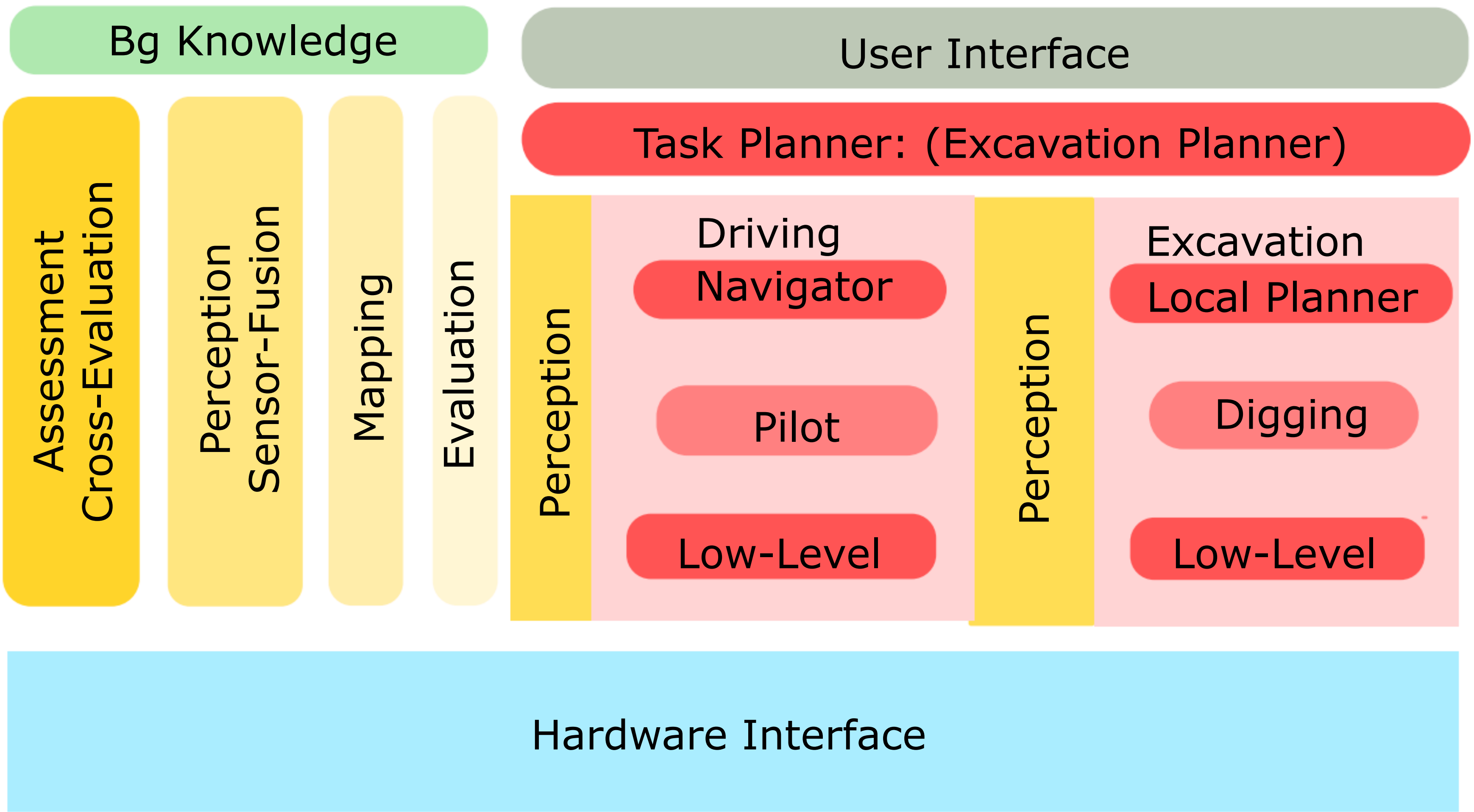
Inverse Kinematic – Reachable Workspace



Excavation Subtasks



Control Architecture



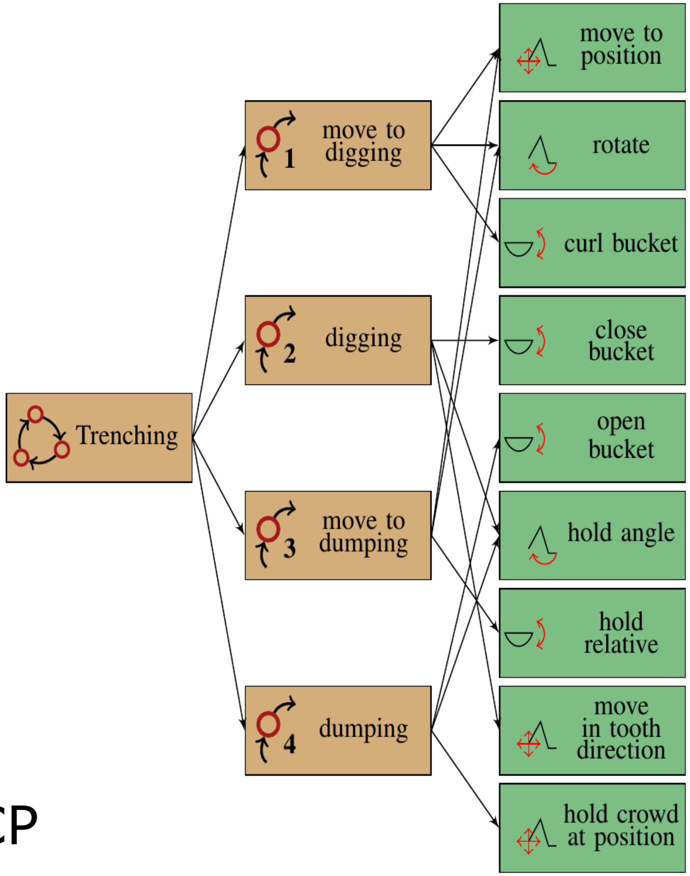
Common Goals

- Bulk handling/loading
- Landscaping (trench digging)
- Workspace extension through automatic offset

- Environment detection
  - Surface rating
  - Other vehicles
  - Obstacles (people)
  - Workspace Details
  - Machine status
  - Position/Stability
  - Scoop filling
  - Force feedback

Problems & Solutions

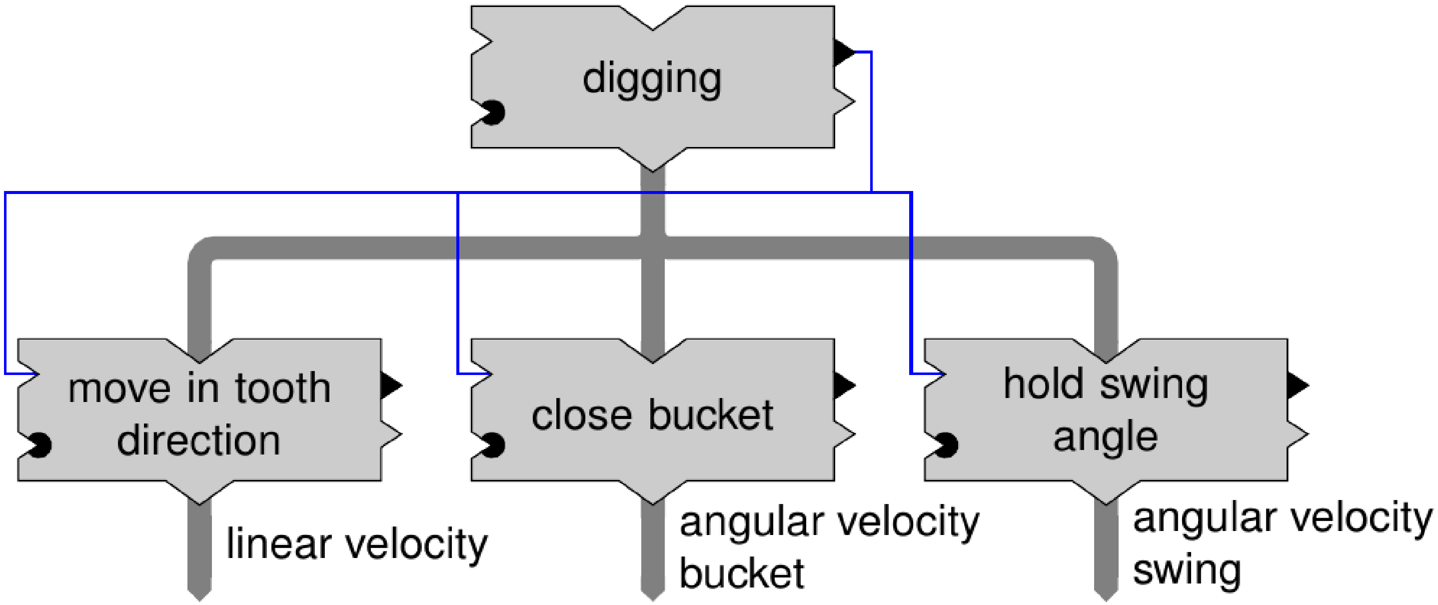
- Strong interaction with environment
- Obstacles
  - Unpredictable, in the ground
  - Adaptivity

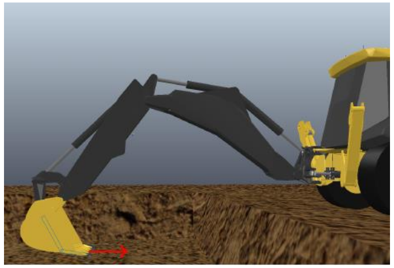


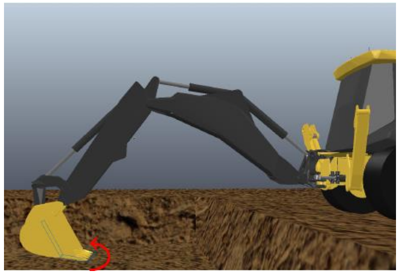
Behavioural Approaches

- Inverse kinematics
- Trajectory tracking/point approach
- Web of motion primitives
- first joint space/Cartesian space TCP
  - extended by digging/shoveling primitives (replaces trajectories)

Example Phase: Digging



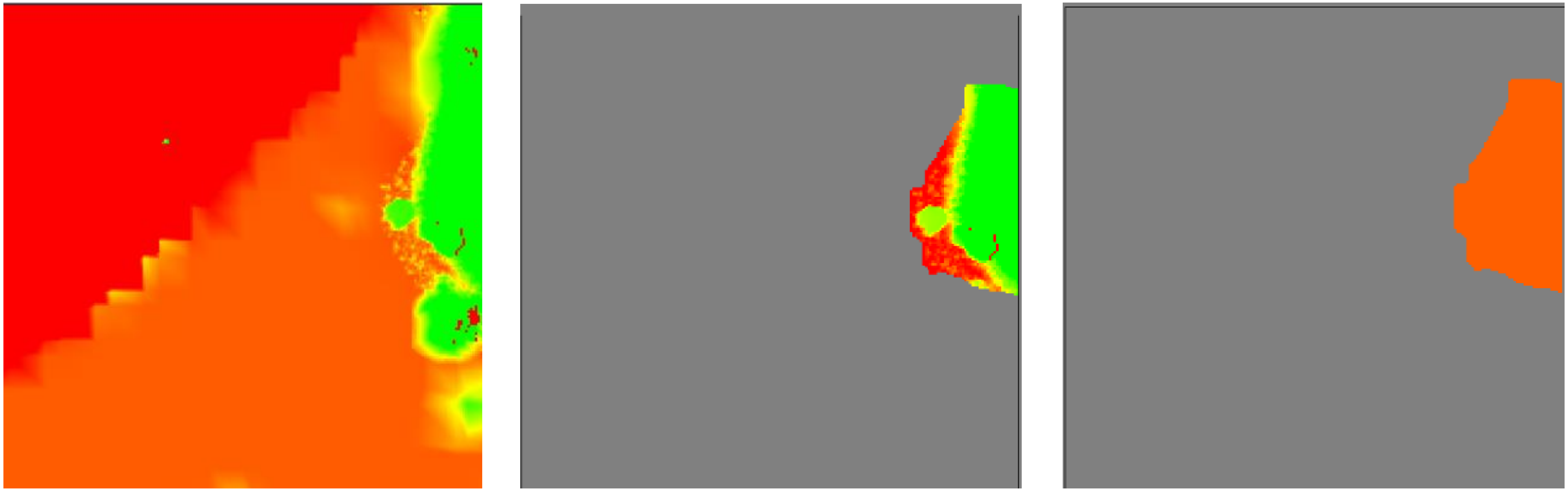




Planning Algorithm: Optimal Working Area Partition

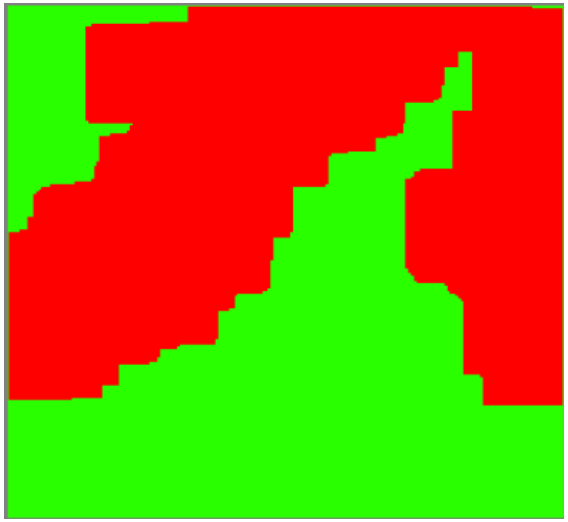
- Size of the excavation volume exceeds the range of an excavator
  - $\Longrightarrow$ Divide the excavation area into smaller pieces.
- Such a partition should be done as most optimal as possible.
- Set Cover Problem is NP-complete
  - $\Longrightarrow$ No solution to find the optimal covering set.
  - $\Longrightarrow$ Approximation Algorithms (greedy Algorithm)

Optimal Working Area Partition

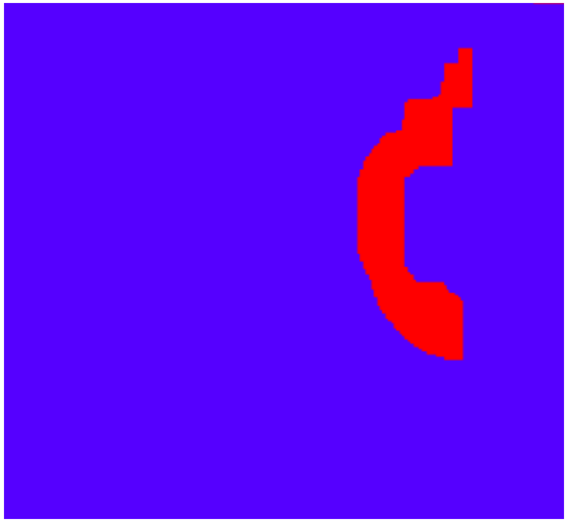


(a) Environment Map (b) Excavation Target (c) Excavation Map

Stand Candidate Evaluation

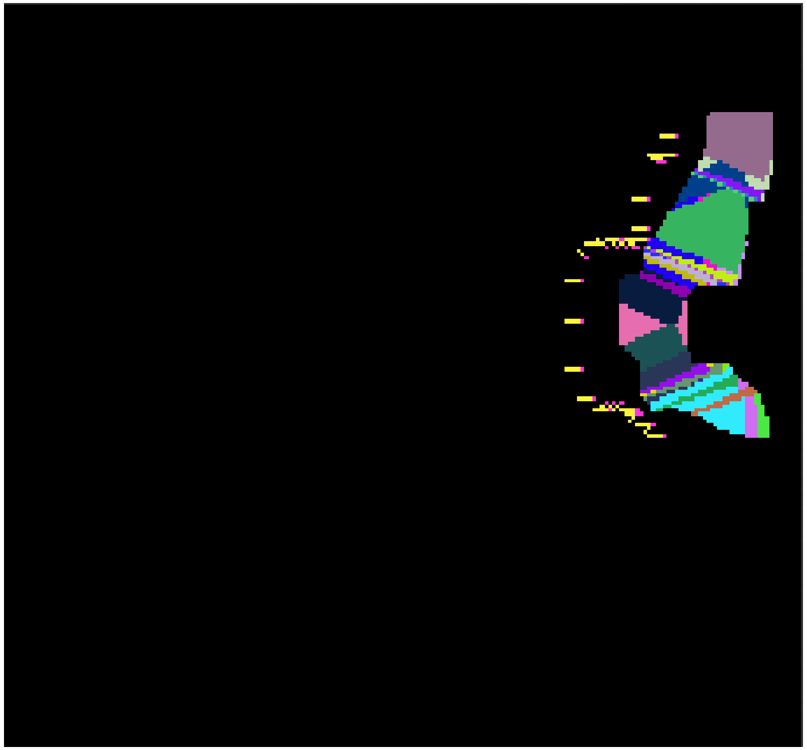


(a) Accessible Positions



(b) Stand Positions

Digging Starting Point Determination using Rating Functions



Partitioning Result

Final Result