Robotic assembly using impedance control and in-hand 3D perception

James Watson[1,2], Austin Miller[2] and Nikolaus Correll[1,2]

[1]University of Colorado at Boulder

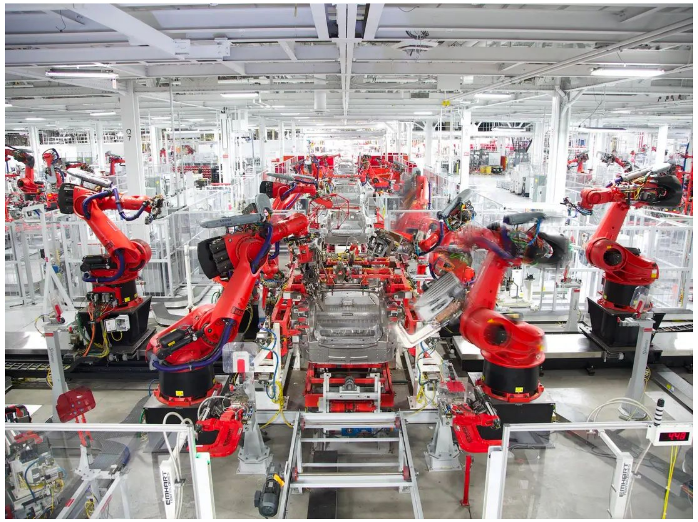
[2]Robotic Materials Inc.

Challenge: if its worth it, built a machine

Manual assembly

Shared autonomy

Fully autonomous



Increasing quantity

As soon as you make enough items, a custom machine maximizes throughput

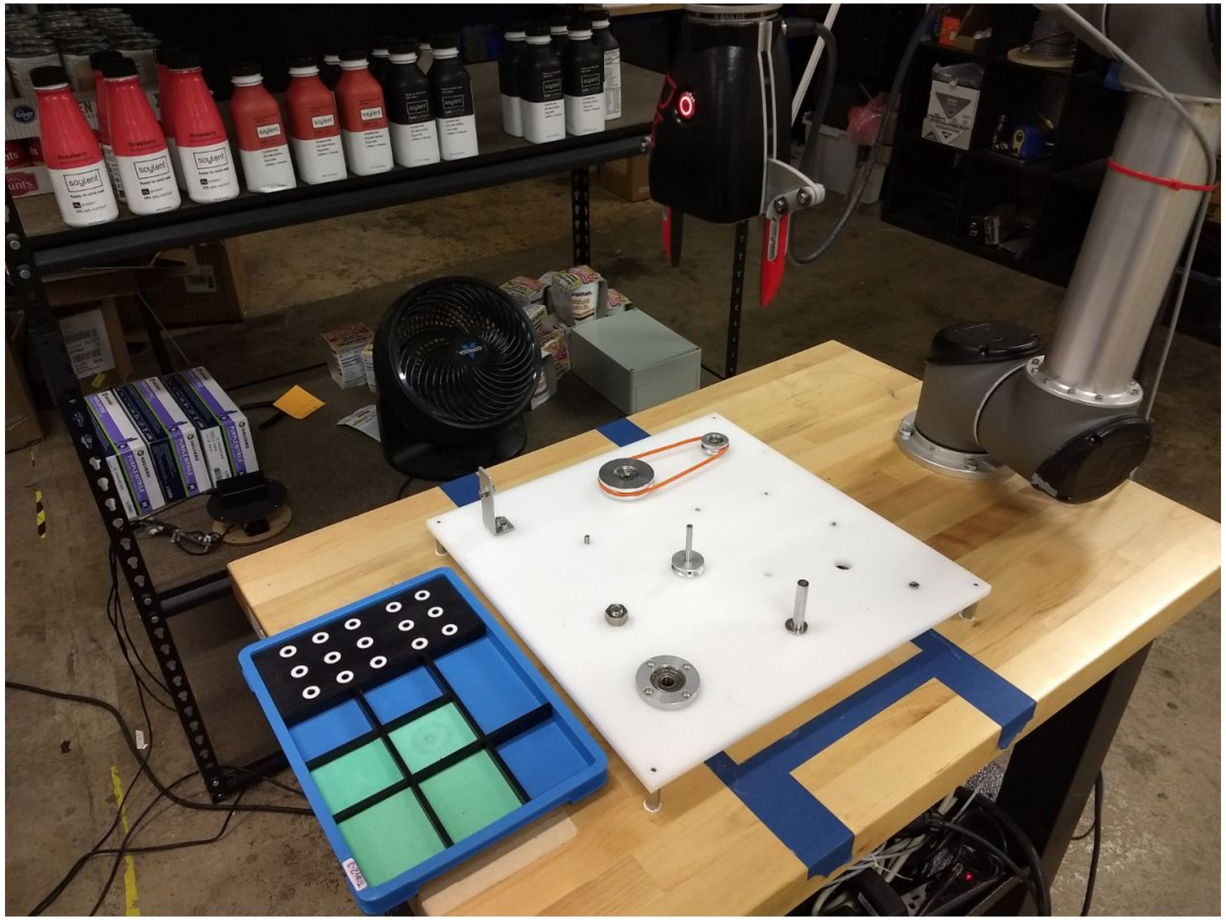
Drivers for "level 5" automation

- Most people don't sell enough to justify building a custom machine -> they need one machine to do multiple things
- Time to setup a production system needs to be minimized
- Tasks with a high degree of automation might only need sporadic tending
- Future: automated maintenance at home, work, and in the field

There is demand for human-like general manipulation.

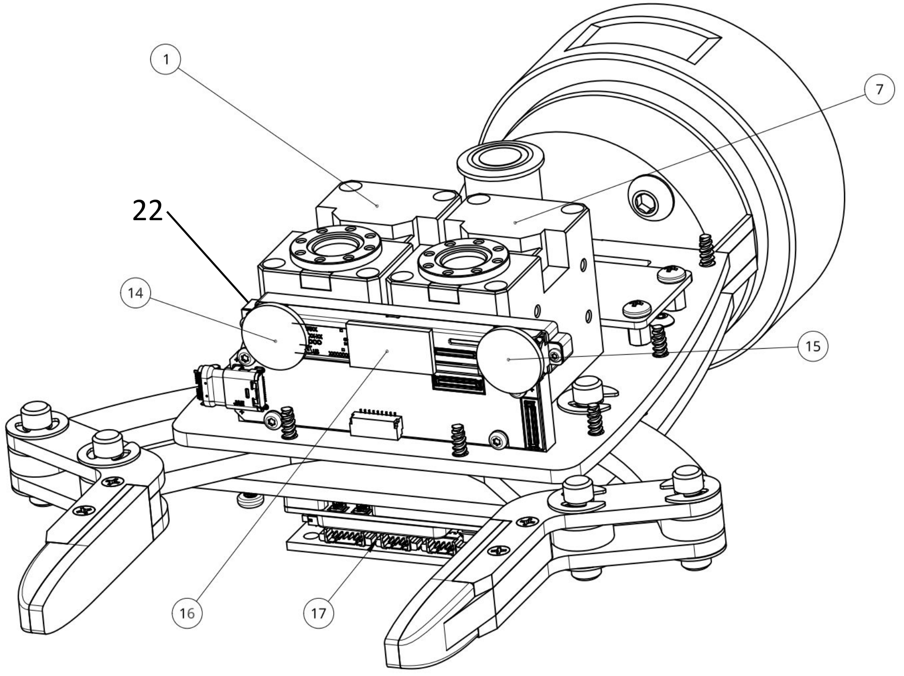
World Robot Summit Plate Assembly

- Assembly of standard machine parts
- Initial pose only roughly known
- Assembly plate can move in-between steps
- At WRS: parts on a kitting mat
- Today: parts presented in ”kitting tray”



Hardware

- UR5 robot with Optoforce load cell
- Robotic Materials SmartHand
  - Intel Realsense
  - Nvidia Jetson
  - Individually impedance-controlled fingers
- Leveraging open-source tools and Python
- Eye-in-hand: constant calibration error
- Stereo depth images as close as 11cm

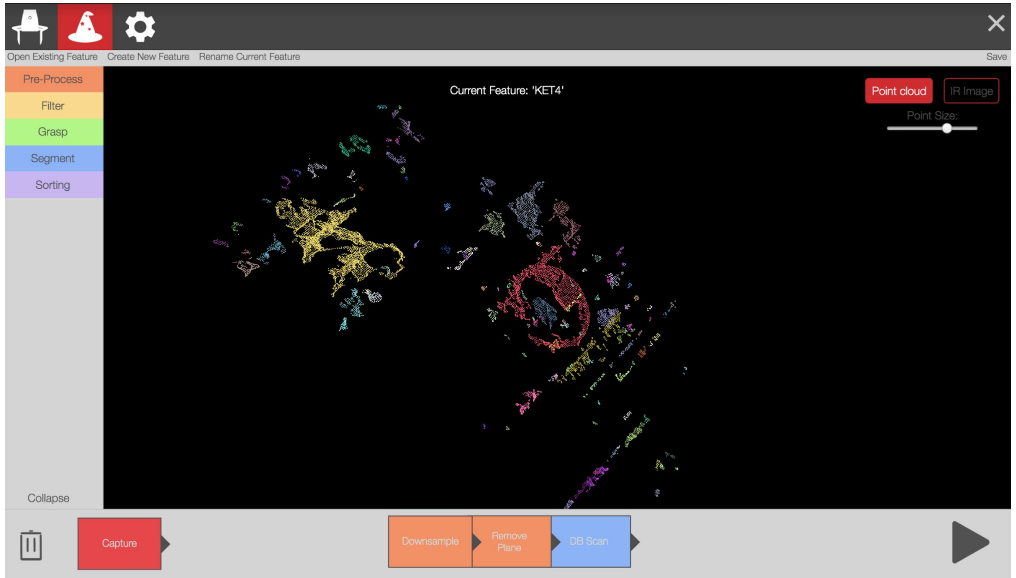


Approach

- Define “features” in the environment using 2D and 3D vision
- Define assemblies in terms of

  feature_1 -> assembly action -> feature_2

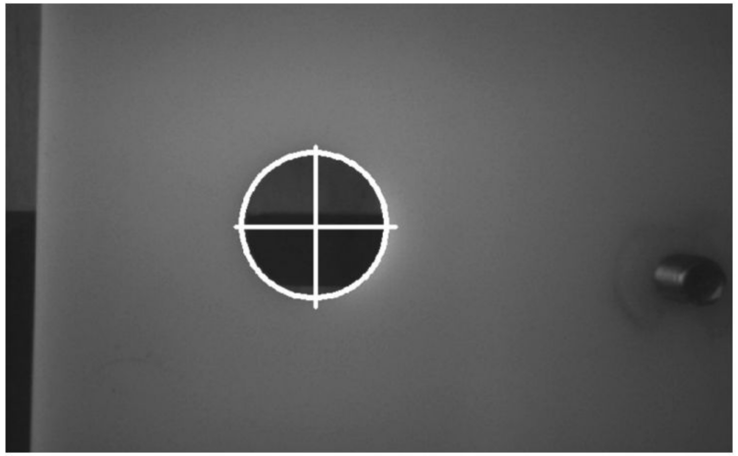
- Use force and torque measurement to define state transitions

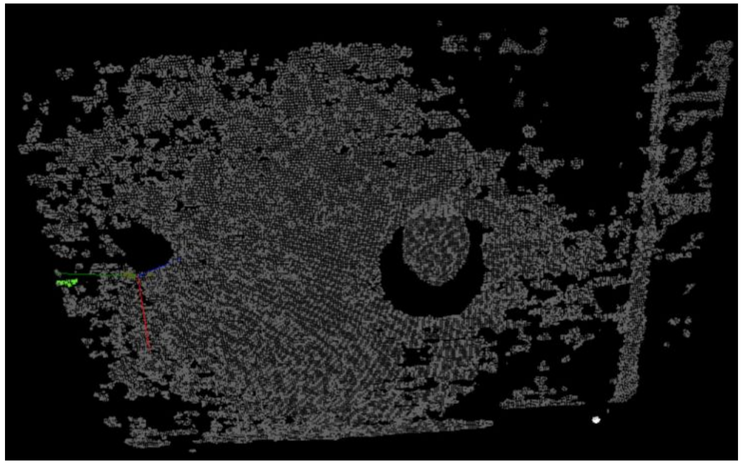


“Feature editor”

Feature detection

- Find circular features (holes) using Hough transform in the image space
- Find pegs using point cloud features





Hole Dia	7cm height	17cm height	27cm height
9mm	0.92	0.99	1.00
17mm	0.59	1.00	1.00
35mm	0.96	1.00	1.00

Spiral-search

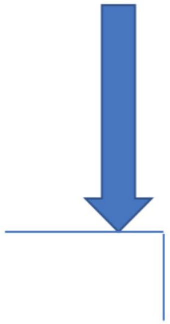
Algorithm 1 Algorithm for inserting a part using a spiral movement

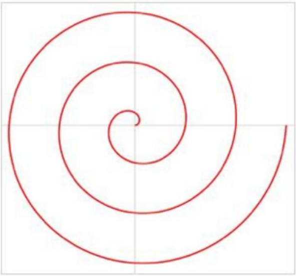
procedure INSERTPARTSPIRAL($\vec{x}_i$, Δz, $F_t = 1$, $F_d = 1$, $F_i = 2$, Δ_{max})

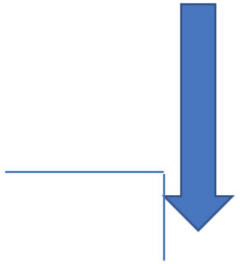
    function MAXDOWNFORCE(f) ▷ Used as a stopping criterion when moving down
        return $GetWristForce(Z) < f$
    end function

    function MAXSPIRALFORCES ▷ Used as a stopping criterin during spiraling
        return $(\|GetWristTorque(X)\| > 0.9) \vee (\|GetWristTorque(Y)\| > 0.9) \vee (GetWristForce(Z) > -F_d)$
    end function

    MoveAbs $(\vec{x}_i + [0, 0, \Delta z, 0, 0, 0])$
    MoveRel $([0, 0, -\Delta_{max}, 0, 0, 0], v = 0.01) \leftarrow$ MAXDOWNFORCE$(-F_t)$
    MoveSpiral$(x_0, y_0, \Delta s = 0.00001, r_{max} = 0.004, v = 0.002, a = 0.5) \leftarrow$ MAXSPIRALFORCES()
    MoveRel $([0, 0, -\Delta_{max}, 0, 0, 0], v = 0.01) \leftarrow$ MAXDOWNFORCE$(-F_i)$
end procedure







Tilt-based assembly

Algorithm 2 Algorithm for inserting a part using a tilting movement

procedure $\textsc{InsertTilt}(\ \vec{x}_{hole}\ ,\ \Delta z\ ,\ \theta_{tilt}\ ,\ \mathrm{Dia}\ ,\ \Delta x\ ,\ F_{touch}\ ,\ F_{insert}\ ,\ \Delta_{max}\ )$

    MoveAbs $(\vec{x}_{hole} + [0, 0, \Delta z, 0, 0, 0])$

    $x_{offset} \leftarrow \Delta x + \sin \theta_{tilt}$

    MoveRel$(\ [-(x_{offset} + \mathrm{Dia}/4), 0, 0, 0, 0, 0]\ )$

    MoveRel$(\ [0, 0, 0, 0, \theta_{tilt}, 0]\ )$

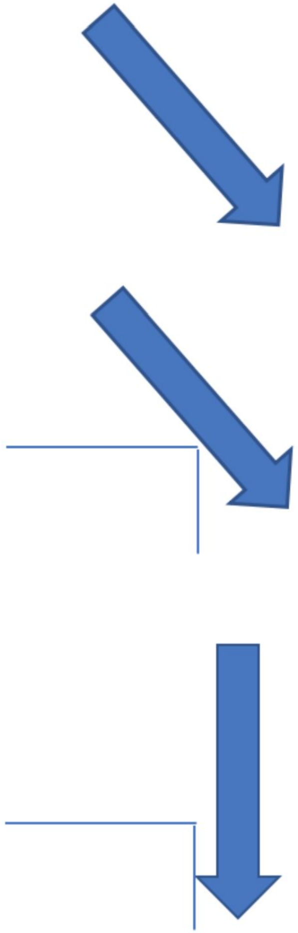
    MoveRel $([0, 0, -\Delta_{max}, 0, 0, 0]) \leftarrow \textsc{MaxDownForce}(-F_{touch})$

    MoveRel$(\ [(x_{offset}+\mathrm{Dia}/4), 0, 0, 0, -\theta_{tilt}, 0]\ ) \leftarrow \textsc{MaxDownForce}(-F_{insert})$

    OpenGripper()

    MoveRel $([0, 0, \Delta_{max}, 0, 0, 0])$

end procedure



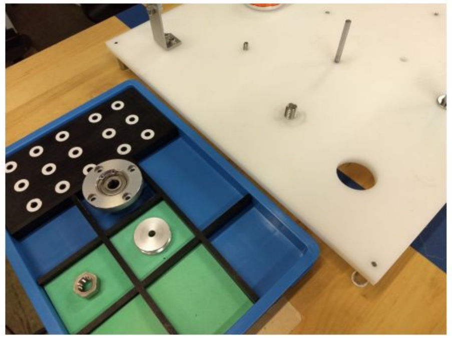
Example: insert bearing algorithm

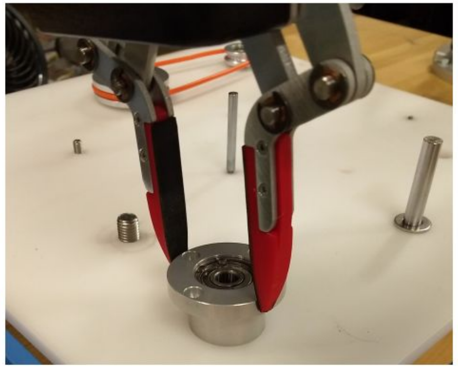
Algorithm 3 Algorithm for the Bearing Insertion Task

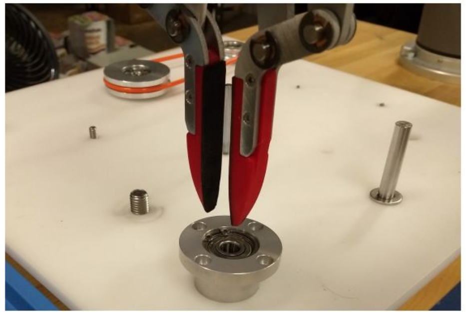
procedure $\textsc{BearingTask}(\ \vec{x}_{BrgView}\ ,\ \vec{x}_{HolView}\ ,\ \mathrm{Dia}_{Bearing}\ ,\ \mathrm{Dia}_{Hole}\ ,\ z_{view}\ ,\ z_{PickDepth}\ ,\ \Delta z\ ,\ \theta_{tilt}\ ,\ F_{touch}\ ,\ F_{insert}\ ,\ \Delta_{max}\ ,\ d_{fingerSep}\ ,\ \vec{x}_{safe}\ )$

    MoveAbs($\vec{x}_{BrgView}$)
    $\vec{x}_{BrgLoc} \leftarrow \textsc{CircleLocator}(\ \textsc{Dia}_{Bearing}\ ,\ z_{view}\ )$
    MoveAbs($\vec{x}_{HolView}$)
    $\vec{x}_{HolLoc} \leftarrow \textsc{CircleLocator}(\ \textsc{Dia}_{Hole}\ ,\ z_{view}\ )$
    Pickpart($\vec{x}_{BrgLoc}$, $\mathrm{Dia}_{Bearing}$, $z_{PickDepth}$)
    InsertTilt($\vec{x}_{HolLoc}$, Δz , θ_{tilt} , Dia_{Hole} , Δx , F_{touch} , F_{insert} , Δ_{max})
    OpenGripper()
    SetGripperOpen($d_{fingerSep}$)
    TampWithForceLimit($\vec{x}_{HolLoc}$, Δz , F_{touch})
    MoveAbs($\vec{x}_{safe}$)

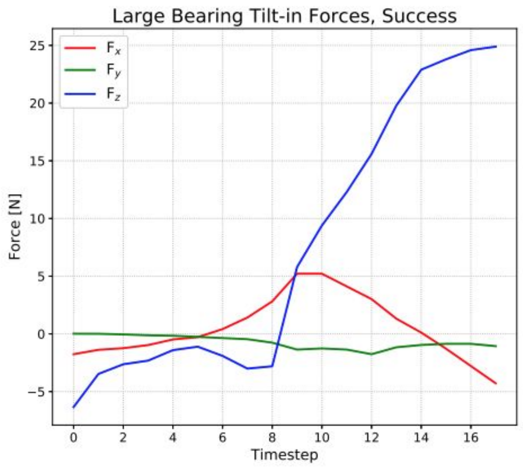
end procedure

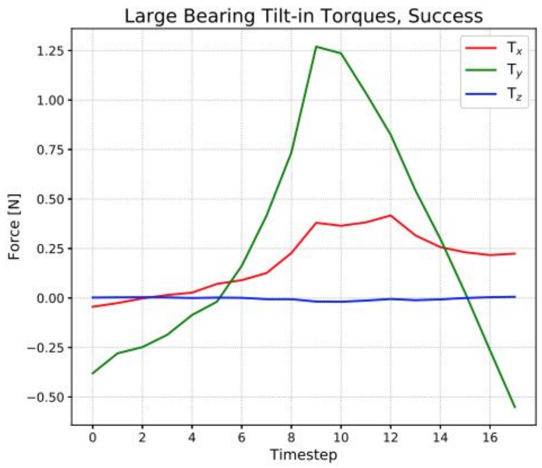


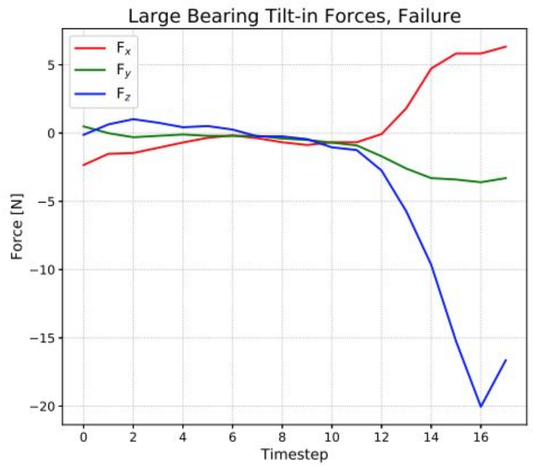


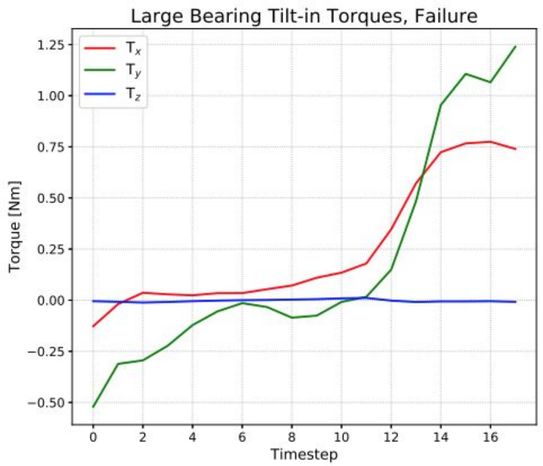


Results: bearing assembly









Task	Trials	Success	Rate
Large Bearing	20	13	0.65
Small Pulley	20	13	0.65
Stud	20	7	0.35

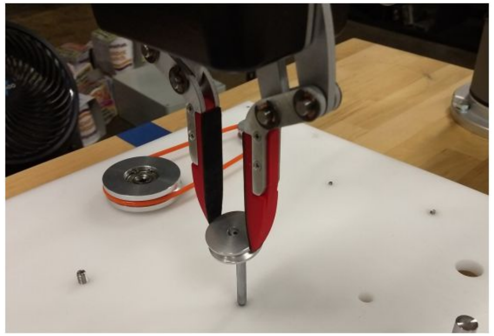
Example: insert small pulley

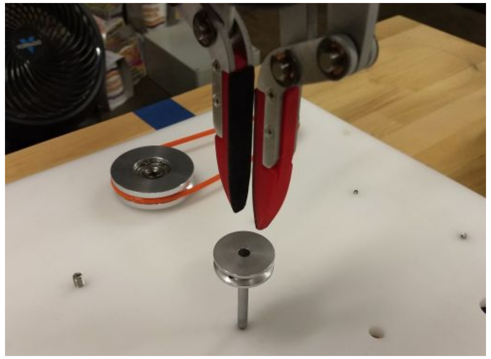
Algorithm 4 Algorithm for the Small Pulley Task

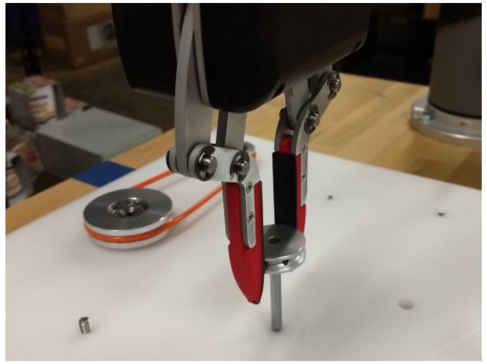
procedure PULLEYTASK($\vec{x}_{ShaftView}$, $\vec{x}_{PullyView}$, Dia_{Shaft} , Dia_{Pulley} , $z_{PickDepth}$, Δz , $F_t = 1$, $F_d = 1$, $F_i = 2$, Δ_{max} , $d_{TampOffset}$, F_{touch} , $d_{fingerSep}$, d_{offset} , z_{grasp} , $\vec{x}_{safe}$)

    MoveAbs($\vec{x}_{ShaftView}$)
    $\vec{x}_{ShftLoc} \leftarrow$ CIRCLELOCATOR(DIA_{Shaft} , z_{view})
    MoveAbs($\vec{x}_{PullyView}$)
    $\vec{x}_{PulyLoc} \leftarrow$ CIRCLELOCATOR(DIA_{Pulley} , z_{view})
    Pickpart($\vec{x}_{PulyLoc}$, Dia_{Pulley} , $z_{PickDepth}$)
    InsertPartSpiral($\vec{x}_{ShftLoc}, \Delta z, F_t = 1, F_d = 1, F_i = 2, \Delta_{max}$)
    MoveAbs($\vec{x}_{safe}$)
    SetGripperOpen($d_{fingerSep}$)
    TampWithForceLimit($\vec{x}_{ShftLoc} + [0, -d_{offset}, 0, 0, 0, 0]$, Δz , F_{touch})
    TampWithForceLimit($\vec{x}_{ShftLoc} + [0, d_{offset}, 0, 0, 0, 0]$, Δz , F_{touch})
    TampWithForceLimit($\vec{x}_{ShftLoc}$, Δz , F_{touch})
    Twist($\vec{x}_{ShftLoc}$, θ_{osc} , N_{osc})
    MoveAbs($\vec{x}_{safe}$)

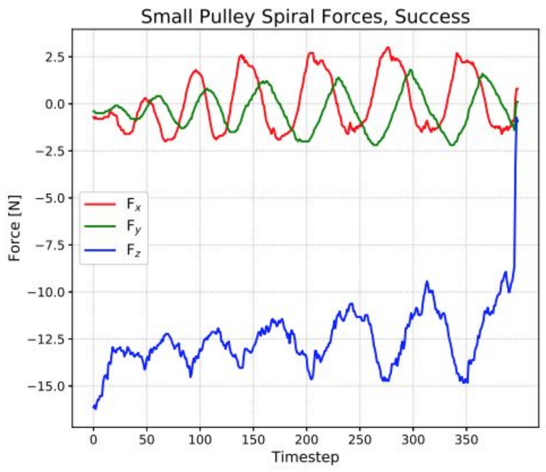
end procedure

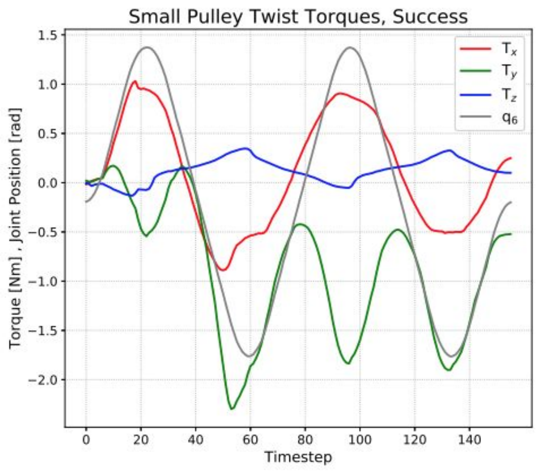


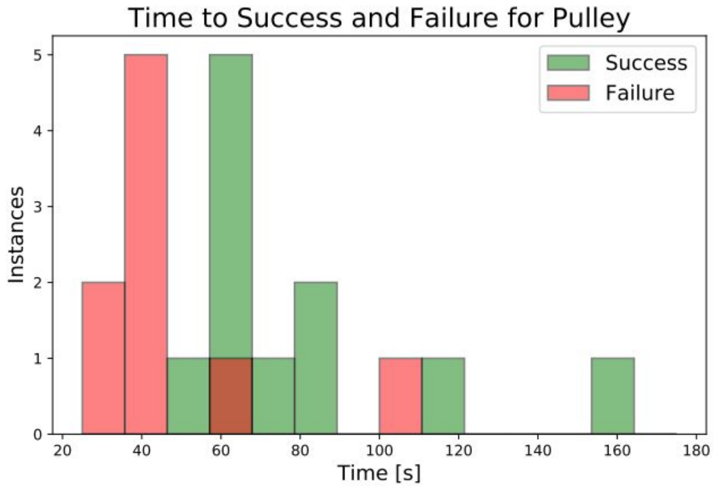


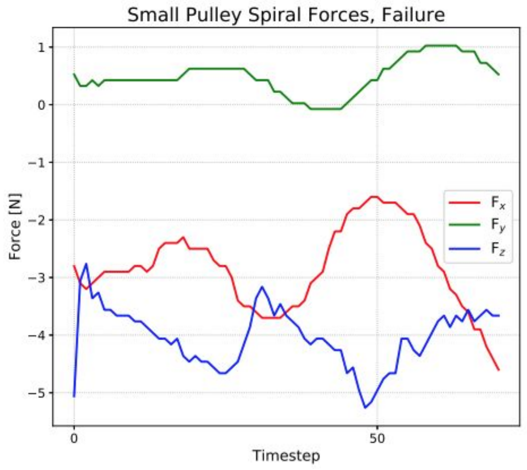


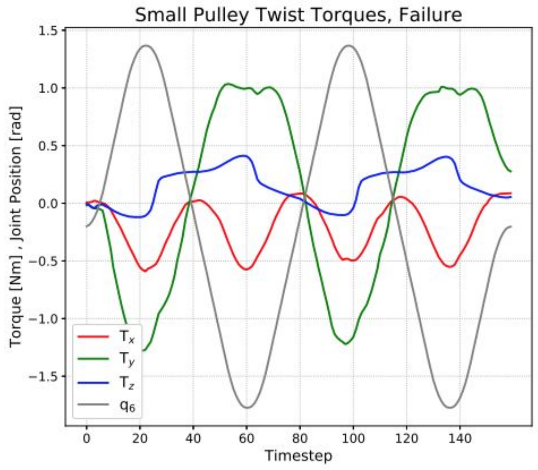
Results: Pulley assembly











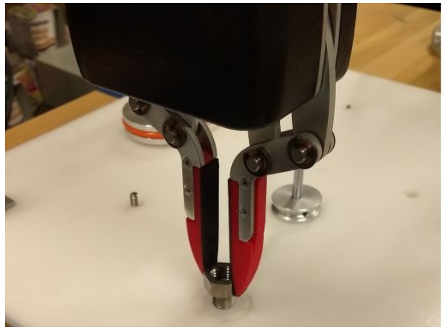
Task	**Trials**	**Success**	**Rate**
Large Bearing	20	13	0.65
Small Pulley	20	13	0.65
Stud	20	7	0.35

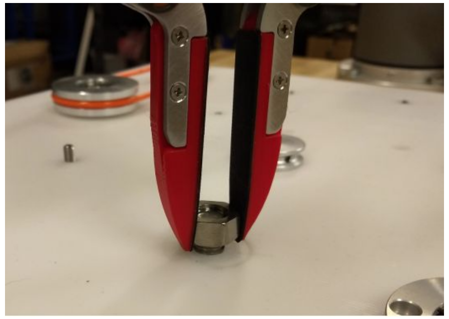
Example: nut threading

Algorithm 5 Algorithm for the Nut Threading Task

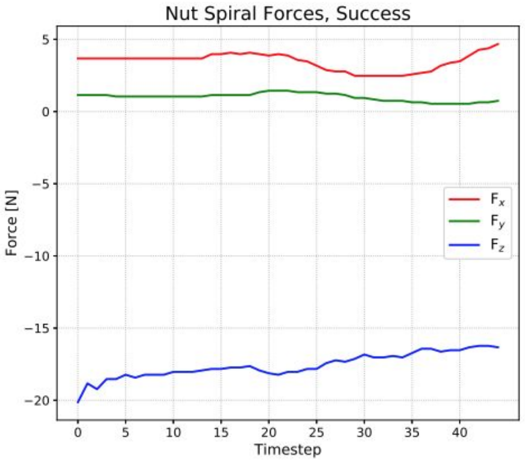
procedure NUTTHREADING($\vec{x}_{StudView}$, $\vec{x}_{NutView}$, Dia_{Stud} , Dia_{Hole} , Dia_{Nut} , $z_{PickDepth}$, Δz , $F_t = 4$, $F_d = 4$, $F_i = 2$, Δ_{max} , N_{flats} , $T_{z,limit}$, d_{pitch} $\vec{x}_{safe}$)

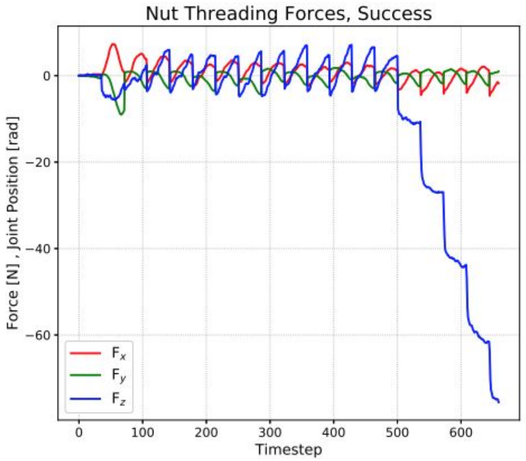
    MoveAbs($\vec{x}_{StudView}$)
    $\vec{x}_{StudLoc} \leftarrow$ CIRCLELOCATOR(DIA_{Stud} , z_{view})
    MoveAbs($\vec{x}_{NutView}$)
    $\vec{x}_{NutLoc} \leftarrow$ CIRCLELOCATOR(DIA_{Hole} , z_{view})
    Pickpart($\vec{x}_{NutLoc}$, Dia_{Nut} , $z_{PickDepth}$)
    InsertPartSpiral($\vec{x}_{StudLoc}$, Δz, $F_t = 4$, $F_d = 4$, $F_i = 2$, Δ_{max})
    MoveAbs($\vec{x}_{safe}$)
    OpenGripper()
    Thread($\vec{x}_{StudLoc}$, N_{flats} , $T_{z,limit}$, d_{pitch})
    OpenGripper()
    MoveAbs($\vec{x}_{safe}$)
end procedure

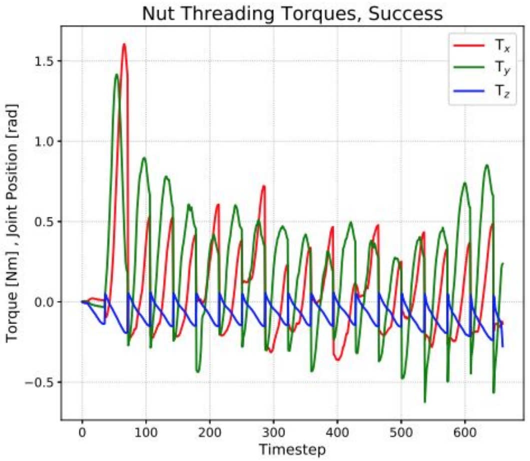


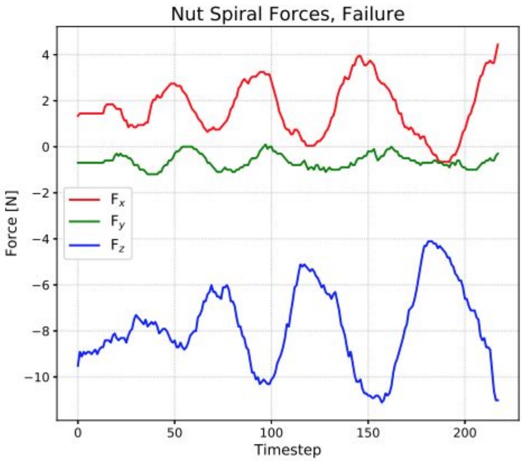


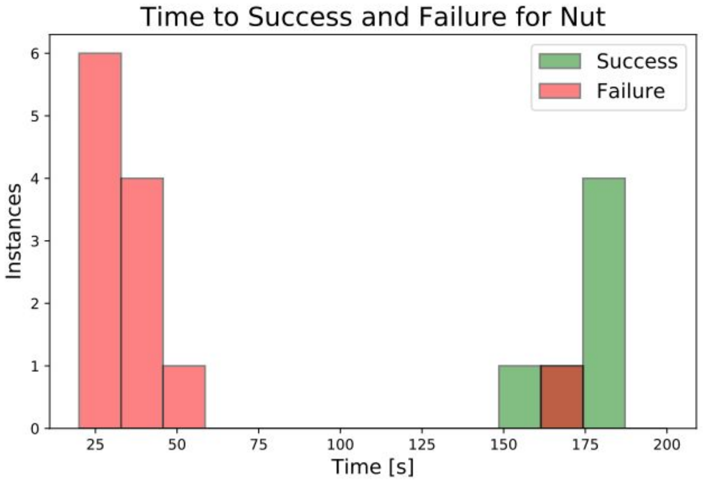
Results: nut threading











Task	Trials	Success	Rate
Large Bearing	20	13	0.65
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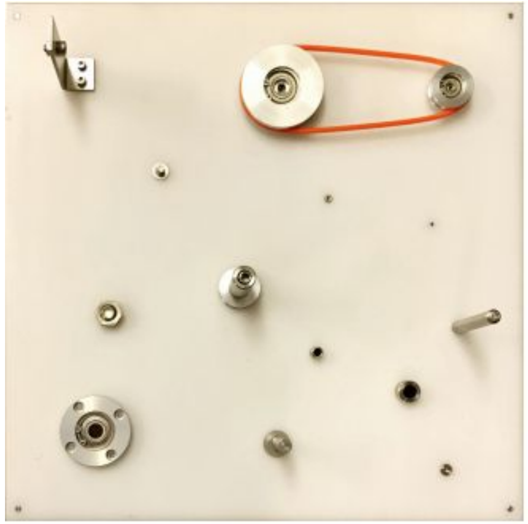
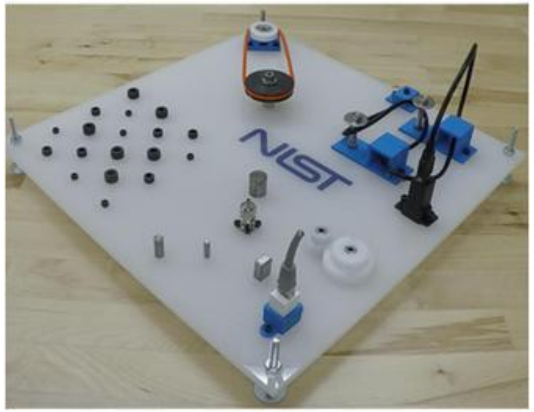
Stud	20	7	0.35

Transferring skills

- Two months full-time to move from WRS to NIST challenge
- New tasks
  - Screwing in screws
  - Rectangular parts
  - Cables
  - Gear meshing
- Disassembly
- Is the space of possible parts finite: yes!
- Is the space of possible assemblies finite: no!





Commercial challenges

- NIST task board disassembly still takes 30+ minutes
- Trading efficiency with availability
- Setting up robot still requires extensive programming and experimentation
- Still better to make a custom machine than employing a general robot

Applied research: commercial = research challenges

What are good metrics?

- Reliability (a custom machine is always better)
- Speed (a custom machine is always better)
- **Versatility** – how?
- Size – why?
- Volume – why?
- Price – compound metric reflecting reliability, speed, versatility

Future work

- Machine learning to prevent failures
- 3D pose estimation
- Combine reactive controllers with semantic reasoning
- Associate nouns and verbs with “common sense” knowledge
  - “Screw”: maintain constant force (press down)
  - “Disassemble”: make sure you hold on to part
  - “Assemble”: make sure assembly does not move
  - …
- Domain-specific language

Acknowledgments

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NIST

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