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1
a)
It is to fulfill the 3-2-1 method. First side 3 points support, second side 2 points support, third side 1 point contact support. This locates the part in space. If this is not fulfilled, you may loose accuracy in the assembly or overconstrain.
I also expected a description of how the 3-2-1 method worked
For something to be classified as a fixture it isimportant to have a structure whichmaintains the relationship between its various elements.It is very important to consider the3-2-1 rule (6 point contact solution). This principlesays that for a workpiece to be completelyconfined it has to be banked against 3 points in oneplane, 2 points in another plane and 1point in the third plane. If we don't follow theserules we will not confine our workpiece in all6 degrees of freedom. Also when building fixtureswe have to build some oversized and ovalholes that will allow the part to expand with heator some other elements and allow us tobring it out of the fixture when processing is done.
b)
We should definitely use modular tooling as we areworking with prototypes. Fromprototypes we can expect some changes in what theyare made since that's what prototypesare fore so it doesn't make sense to build a fixednon modular fixture/tooling as we will mostlikely have to change it in the end anyway. Also modulartooling allows us to change duringthe prototyping phase so we can try out differentsolutions as well and see what works bestfor our specific use case. As we said in the lecturesmodular fixtures take shorter time toconfigure and assemble, reduce inventory holding,and offer good repeatability andaccuracy. They also simplify assembly. But to noteis that these parts are very big and heavyso an aluminium fixture might not be sufficient sowe could use a solution with BoxJoint asdescribed in the lectures to get a more rigid modularfixture/tooling.
Low volume should suggest using modular tooling to enable re-build and re-use

2
a)
ARC welding robots are used since ships are build in steel. Many plates are welded together.
Most likely we would use a classical industrial armrobot that would most likely dosteel plate handling and welding. We need industrialrobots as this tasks require highload capacity and high accuracy to be able to assurea high quality product. Theplates are very heavy so a collaborative robot isnot an option as they can only liftaround 15kg, so the only reasonable option is theclassical industrial robot as in thecar industry. Also in addition to the big weldingand handling robots, some smallerones for quality control could be used that wouldgo around the boat autonomously(ie. a drone) and try to find imperfections of deformationson the ship.
b)
Having one program per plate assembly and there are many plate assemblies, it is well worth to invest development on process-oriented programming where programs are created automatically from product parameters.
Every assembly was unique. New program for every assembly. Therefore we needed Process-oriented programming.
As each ship is unique, a higher abstraction level than robot oriented isvery advantageous. Robot oriented programming for unique parts requiresthe programmer to more or less rewrite the robot program for each newproduct. By using object oriented programming or task oriented program-ming, the process of programming for welding ships would be greatly sim-plified. This would probably require robot manufacturers/programmingsoftware developers to implement new abstraction levels for programming,which could be aided by machine learning. (Philip Lees 2021)

3
Unitmate. First customer was GM. They had hazardous environment, wearout of humans, and many repetitive tasks. It was more cost-effective using robots.

4
See the course material on Canvas

5
Stands for Intelligently Moving Manikin.

6
The Gartner hype cycle describes the maturity of emerging technologies. Usually higher and higher expectations build up for a new technology over time, as speculations about it occur. After some time, it is found that many of these uses are not possible of are difficult to achieve, lowering the hype. After some more time, the applications where the technology works well are discovered and implemented, which leads to a mature state of the technology in question.
In Initial stages all the technologies will look like or presentedas the solutions of the current problemsbecause of the hype created by them when they were launched.But later it will berealizedthat those technologiesare not the final solutionsof the problemsand eventually the hype goes down.This Gartner Hype cycle is that graph which shows how the expectations on each technologychange over the time.

7
It was socially not accepted. People were afraid of constant privacy violations.

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8
Motoman is the product, Yaskawa is the company

9
For Yaskawa, it is a holistic engineering philosophy

10
Laser as sensor - initial start point search and real-time tracking during welding.
Laser as welding source - higher effiency/speed, easier to achieve full penetration from one sided welding, without beveling the plate.

They used lasers in order to buide the robot driving the welding, this technique is called “laser seam welding”

11
Must include:

- Sensor integrated to increase the number of sences
- Machine learning to speed-up programming
- Collaboration to avoid fences and lower the cost

12 and 13
See comments in the exam and the course material on Canvas

14.

```
-- No declarations needed
-- Definition main subroutine
MAIN:SUBR;

-- Subroutines
FIXAFULLRAD:SUBR;
WRITEO(9, 1);
WAITI(1, 1, 0);
WAITI(2, 1, 0);
WAITI(3, 1, 0);
WAITI(4, 1, 0);
WRITEO(9, 0);
END;

FIXAGRIS:SUBR;
PICKROCK;
TESTI(4, 0, GRIS4);
TESTI(3, 0, GRIS3);
TESTI(2, 0, GRIS2);
SORTROCK(1);
BRANCH(SLUT);
GRIS2:;
SORTROCK(2);
BRANCH(SLUT);
GRIS3:;
SORTROCK(3);
BRANCH(SLUT);
GRIS4:;
SORTROCK(4);
SLUT:;
END;
```

SOME ALTERNATIVES EXISTS, FOR EXAMPLE:

```
FIXAGRIS:SUBR;
PICKROCK;
TESTI(2, 1, GRIS1);
TESTI(3, 1, GRIS2);
TESTI(4, 1, GRIS3);
SORTROCK(4);
BRANCH(SLUT);
GRIS3:;
SORTROCK(3);
BRANCH(SLUT);
GRIS2:;
SORTROCK(2);
BRANCH(SLUT);
GRIS1:;
SORTROCK(1);
SLUT:;
END;
```

```
-- Main program

FIXAFULLRAD;
FIXAGRIS;
END;
```

15

a) $T = Rot(z,\theta_1)Trans(z,a_2)Trans(x,b)Rot(x,180^\circ)Rot(y,\theta_3)Trans(z,d)Rot(x,90^\circ)Rot(z,90^\circ)Rot(z,\theta_4)Trans(z,e)$

Note: Other alternatives gives the same result

$$T = \begin{bmatrix} c_1 & -s_1 & 0 & bc_1 \\ s_1 & c_1 & 0 & bs_1 \\ 0 & 0 & 1 & a_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c_3 & 0 & s_3 & 0 \\ 0 & -1 & 0 & 0 \\ s_3 & 0 & -c_3 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} -s_4 & -c_4 & 0 & 0 \\ 0 & 0 & -1 & -e \\ c_4 & -s_4 & 0 & d \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T = \begin{bmatrix} c_1c_3 & s_1 & c_1s_3 & bc_1 \\ s_1c_3 & -c_1 & s_1s_3 & bs_1 \\ s_3 & 0 & -c_3 & a_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} -s_4 & -c_4 & 0 & 0 \\ 0 & 0 & -1 & -e \\ c_4 & -s_4 & 0 & d \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T = \begin{bmatrix} c_1(s_3c_4-c_3s_4) & c_1(-c_3c_4-s_3s_4) & -s_1 & bc_1+dc_1s_3 - es_1 \\ s_1(s_3c_4-c_3s_4) & s_1(-c_3c_4-s_3s_4) & c_1 & bs_1+ds_1s_3 + ec_1 \\ -s_3s_4-c_3c_4 & -s_3c_4+c_3s_4 & 0 & a_2 - dc_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T = \begin{bmatrix} c_1s_{3-4} & -c_1c_{3-4} & -s_1 & bc_1+dc_1s_3 - es_1 \\ s_1s_{3-4} & -s_1c_{3-4} & c_1 & bs_1+ds_1s_3 + ec_1 \\ -c_{3-4} & -s_{3-4} & 0 & a_2 - dc_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

b) The first two Euler angles requires that $\theta_1 = 90^\circ$. Then look at the geometry in the YZ-plane. There are two possible solutions with the stated workspace:

$\theta_1 = 90^\circ$, $a_2 = 30$m, $\theta_3 = 30^\circ$, $\theta_4 = -30^\circ$

$\theta_1 = 90^\circ$, $a_2 = (30 - \sqrt{3}d)$m, $\theta_3 = 150^\circ$, $\theta_4 = 90^\circ$

16 Solution:

a) The purpose of the fourth row is to get the angular velocity $\boldsymbol{\omega_z}$ of the TCS about the baseframe's Z-axis. This is done by multiplying it with the corresponding joint velocities:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \omega_z \end{bmatrix} = J \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{d}_3 \\ \dot{\theta}_4 \end{bmatrix}$$

Theoretically/mathematically the elements of the fourth row are the partial derivatives we get when we differentiate the angular displacement of the TCS about the baseframe's Z-axis with respect to each joint variable.

For the IBM7545 the elements corresponds to each joint's rotation unit vector w r t the baseframe's Z-axis. The 1st and 2nd one are parallel with the baseframe's Z-axis (=1$\mathbf{e_z}$). The 4th joint has opposite direction (=-1$\mathbf{e_z}$). Prismatic joints doesn't contribute to angular displacement (= 0).

Values of the third prismatic joint $\mathbf{d_3}$ are not present in the Jacobian since it becomes a constant (=-1) when differentiating the Z displacement. $\boldsymbol{\theta_4}$ would appear if we introduce a TCP with XY-offsets. But the TCP is located on the rotation axis of the last joint and so the translational motion is independent of $\boldsymbol{\theta_4}$. The angular motion dependency of $\boldsymbol{\theta_4}$ is the constant rotation unit vector explained above (=-1$\mathbf{e_z}$).

b)

$$J^{-1} = \frac{1}{abs_2}\begin{bmatrix} bc_{12} & bs_{12} & 0 & 0 \\ -(ac_1 + bc_{12}) & -(as_1 + bs_{12}) & 0 & 0 \\ 0 & 0 & -abs_2 & 0 \\ -ac_1 & -as_1 & 0 & -abs_2 \end{bmatrix}$$

$|J|$ = cofactor expansion by row = $-ab(s_1c_{12} - c_1s_{12}) = ab\sin\theta_2$

$|J| = ab\sin\theta_2$ => singularity in $\theta_2 = 0^\circ$ ($\theta_2 = 180^\circ$ is outside the workspace)

Calculation details:

$J^{-1}_{11} = \begin{vmatrix} bc_{12} & 0 & 0 \\ 0 & -1 & 0 \\ 1 & 0 & -1 \end{vmatrix} = bc_{12}$ $J^{-1}_{12} = -\begin{vmatrix} -bs_{12} & 0 & 0 \\ 0 & -1 & 0 \\ 1 & 0 & -1 \end{vmatrix} = bs_{12}$ $J^{-1}_{13} = \begin{vmatrix} -bs_{12} & 0 & 0 \\ bc_{12} & 0 & 0 \\ 1 & 0 & -1 \end{vmatrix} = 0$ $J^{-1}_{14} = -\begin{vmatrix} -bs_{12} & 0 & 0 \\ bc_{12} & 0 & 0 \\ 0 & -1 & 0 \end{vmatrix} = 0$

$J^{-1}_{21} = -\begin{vmatrix} ac_1+bc_{12} & 0 & 0 \\ 0 & -1 & 0 \\ 1 & 0 & -1 \end{vmatrix} = -(ac_1+bc_{12})$ $J^{-1}_{22} = \begin{vmatrix} -(as_1+bs_{12}) & 0 & 0 \\ 0 & -1 & 0 \\ 1 & 0 & -1 \end{vmatrix} = -(as_1+bs_{12})$ $J^{-1}_{23} = -\begin{vmatrix} -(as_1+bs_{12}) & 0 & 0 \\ ac_1+bc_{12} & 0 & 0 \\ 1 & 0 & -1 \end{vmatrix} = 0$ $J^{-1}_{24} = \begin{vmatrix} -(as_1+bs_{12}) & 0 & 0 \\ ac_1+bc_{12} & 0 & 0 \\ 0 & -1 & 0 \end{vmatrix} = 0$

$J^{-1}_{31} = \begin{vmatrix} ac_1+bc_{12} & bc_{12} & 0 \\ 0 & 0 & 0 \\ 1 & 1 & -1 \end{vmatrix} = 0$ $J^{-1}_{32} = -\begin{vmatrix} -(as_1+bs_{12}) & -bs_{12} & 0 \\ 0 & 0 & 0 \\ 1 & 1 & -1 \end{vmatrix} = 0$ $J^{-1}_{33} = \begin{vmatrix} -(as_1 + bs_{12}) & -bs_{12} & 0 \\ ac_1 + bc_{12} & bc_{12} & 0 \\ 1 & 1 & -1 \end{vmatrix} = -abs_2$ $J^{-1}_{34} = -\begin{vmatrix} -(as_1 + bs_{12}) & -bs_{12} & 0 \\ ac_1 + bc_{12} & bc_{12} & 0 \\ 0 & 0 & 0 \end{vmatrix} = 0$

$J^{-1}_{41} = -\begin{vmatrix} ac_1+bc_{12} & bc_{12} & 0 \\ 0 & 0 & -1 \\ 1 & 1 & 0 \end{vmatrix} = -ac_1$ $J^{-1}_{42} = \begin{vmatrix} -(as_1+bs_{12}) & -bs_{12} & 0 \\ 0 & 0 & -1 \\ 1 & 1 & 0 \end{vmatrix} = -as_1$ $J^{-1}_{43} = -\begin{vmatrix} -(as_1+bs_{12}) & -bs_{12} & 0 \\ ac_1+bc_{12} & bc_{12} & 0 \\ 1 & 1 & 0 \end{vmatrix} = 0$ $J^{-1}_{44} = \begin{vmatrix} -(as_1+bs_{12}) & -bs_{12} & 0 \\ ac_1+bc_{12} & bc_{12} & 0 \\ 0 & 0 & -1 \end{vmatrix} = -abs_2$