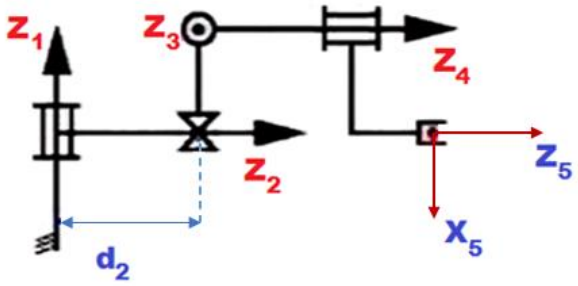
Name: _____
Student number: _____

***Return THIS SHEETS together with your answer sheets***

## ***Question 1 (35%)***

Obtain the modified Denavit-Hartenberg table for the next RPRR manipulator. In a picture show clearly the frame assignment and the DH parameters for each of the links




## ***Question 2 (15%)***

Draw the manipulator which generates the next modified Denavit-Hartenberg table. Draw as well the frame assigned to each of the links

| j | theta | d | a | alpha |
|---|---|---|---|---|
| 1 | q1 | 0.4 | 0 | 0 |
| 2 | q2 | 0 | 0.75 | 0 |
| 3 | q3 | 0 | 0.5 | 0 |

## ***Question 3 (20%)***

Obtain Jacobian matrix for the linear velocities ( $J_{X_P}$) of a manipulator having an homogenous transformation matrix ${}^0T_4$, where frame {4} is the last link frame and $L_1, L_2, L_3, L_4$ are constants

$$ {}^0T_4 = \begin{bmatrix} c_{124} & s_{124} & 0 & L_3c_{12} + L_2c_1 \\ s_{124} & -c_{124} & 0 & L_3s_{12} + L_2s_1 \\ 0 & 0 & -1 & -L_4 + q_3 + L_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

## ***Question 4 (20%)***

In the exercises session a **numerical** algorithm to solve the inverse kinematics of an arbitrary manipulator was reviewed. Explain how it works. Provide the pseudo-code of the algorithm

## ***Question 5 (10%)***

A manipulator is defined by the next modified Denavit-Hartenberg table.

| j | theta | d | a | alpha |
|---|---|---|---|---|
| 1 | q1 | 0.4 | 0 | 0 |
| 2 | q2 | 0 | 0.75 | 0 |
| 3 | q3 | 0 | 0.5 | 0 |

By using the Robotics Toolbox, **provide** the Matlab **code** to achieve the next:

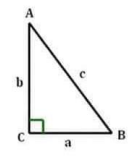
- Define the serial manipulator object
- Compute the forward kinematics of the manipulator for an arbitrary input
- The command to render the manipulator
- The code to compute the inverse kinematics of the manipulator for an arbitrary target

**Support material**

The next material is given as support. Use it if you need it to solve any of the questions

**Trigonometric Functions and Special Angles**

**Trigonometric Functions (Right Triangle)**




**SOH-CAH-TOA**

$\sin = \frac{opposite}{hypoteneuse}$ $\sin A = \frac{a}{c}$ $\sin B = \frac{b}{c}$

$\cos = \frac{adjacent}{hypoteneuse}$ $\cos A = \frac{b}{c}$ $\cos B = \frac{a}{c}$

$\tan = \frac{opposite}{adjacent}$ $\tan A = \frac{a}{b}$ $\tan B = \frac{b}{a}$

**Special Angles**

**Trig Functions of Special Angles (θ)**

| Radians | Degrees | $\sin\theta$ | $\cos\theta$ | $\tan\theta$ |
|---|---|---|---|---|
| 0 | 0° | $\frac{\sqrt{0}}{2} = 0$ | $\frac{\sqrt{4}}{2} = 1$ | $\frac{\sqrt{0}}{\sqrt{4}} = 0$ |
| $\pi/6$ | 30° | $\frac{\sqrt{1}}{2} = \frac{1}{2}$ | $\frac{\sqrt{3}}{2}$ | $\frac{\sqrt{1}}{\sqrt{3}} = \frac{\sqrt{3}}{3}$ |
| $\pi/4$ | 45° | $\frac{\sqrt{2}}{2}$ | $\frac{\sqrt{2}}{2}$ | $\frac{\sqrt{2}}{\sqrt{2}} = 1$ |
| $\pi/3$ | 60° | $\frac{\sqrt{3}}{2}$ | $\frac{\sqrt{1}}{2} = \frac{1}{2}$ | $\frac{\sqrt{3}}{\sqrt{1}} = \sqrt{3}$ |
| $\pi/2$ | 90° | $\frac{\sqrt{4}}{2} = 1$ | $\frac{\sqrt{0}}{2} = 0$ | *undefined* |

Note the patterns in the above table: In the sine column, the numbers 0 to 4 occur in sequence under the radical! The cosine column is the sine column reversed. Tangent = sine ÷ cosine.

**Extra−math**

$$\begin{aligned}
\sin(x\pm y) &= \sin x\cos y \pm \cos x\sin y,\\
\cos(x\pm y) &= \cos x\cos y \mp \sin x\sin y,\\
2\sin x\sin y &= \cos(x-y) - \cos(x+y),\\
2\cos x\cos y &= \cos(x-y) + \cos(x+y),\\
2\sin x\cos y &= \sin(x-y) + \sin(x+y).
\end{aligned}$$