# ENME489C/ENME808M: Problem Set 4
# Forward Kinematics

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Fall 2017

Due Date: Monday 10/2 5 PM

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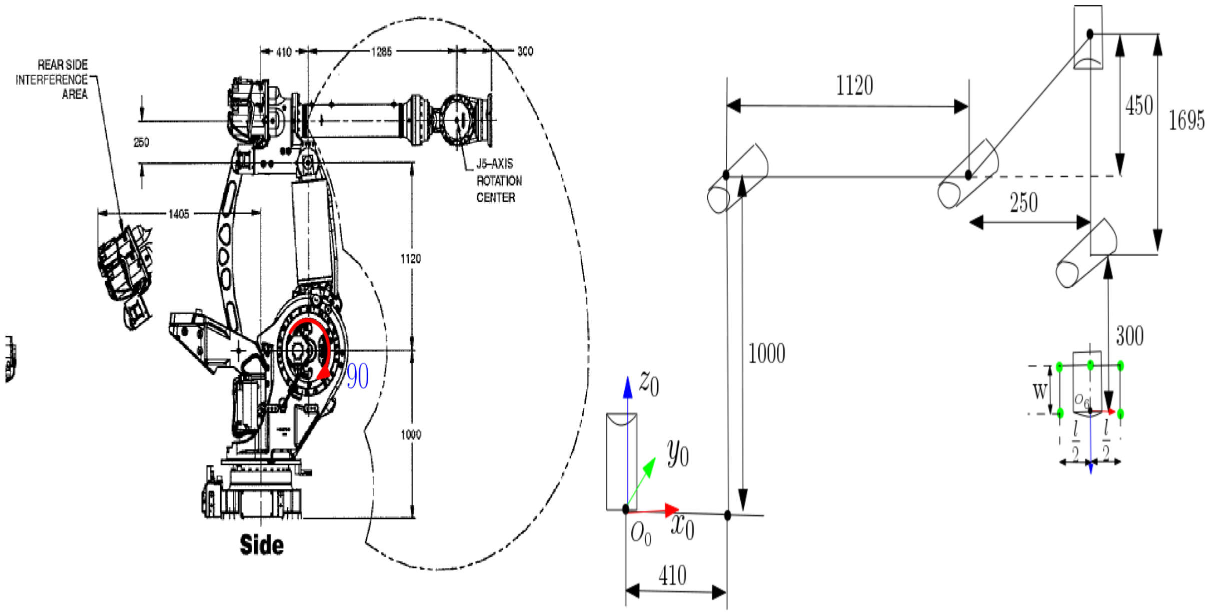
In this problem set, we will study the Forward Kinematics of an Industrial Manipulator, using DH notations. With DH notations we can reduce the parameters for representing the transformations between two frames from six to four. This is accomplished by constraining the X-axis placement of the second frame to be perpendicular and intersecting with the Z-Axis of the previous frame. The transformation can be conveniently represented using four parameters: $a$, $\alpha$, $d$, $\theta$. In this problem set you will learn how to use the Robotic Toolbox in MATLAB to compute forward kinematics and plot your manipulator. You will also learn to write your own MATLAB functions to compute forward kinematics and plot the manipulator. Lastly, you will compare the two results.

## 1 Problem Statement

Figure 1 shows the manipulator diagram of the Fanuc M-900 and the corresponding kinematic diagram. The manipulator is a 6 DOF, Articulated Manipulator (R-R-R) with a spherical wrist (Z-Y-Z). Also, we have given you a simplified kinematic chain approximation of the manipulator. There is gripper with planar geometry attached to the manipulator. We will call the kinematic chain in this form as the home configuration of the manipulator. Notice that we have drawn the kinematic chain after rotating the revolute joint 2 by 90 degrees. We do this for couple of reasons. First, to simplify the DH Frame assignment, so that the DH constraints are satisfied without having to place the link-attached frames at non-intuitive locations. Second, to conform to the way MATLAB's Robotics System Toolbox expects its DH parameters for constructing the manipulator.

The gripper is modeled using five green points as shown in the figure. We can express the coordinates of these points in the end-effector frame defined at origin $O_6$. The coordinates of the five green points can be written in a clockwise manner as follows:

- (-l/2 0 0)
- (-l/2 0 -w)




(a) Manipulator diagram of the Fanuc M-900

(b) Kinematic diagram of the manipulator

Figure 1: Manipulator

- (0 0 -w)
- (l/2 0 -w)
- (l/2 0 0)

## 2 Assignment

Your task in this problem set is to accomplish the following:

1. Assign the frames properly in the provided kinematic chain using DH conventions and construct the DH table for this manipulator (20 points). Perform this task manually on a piece of paper.
2. Using the DH Parameters Support in MATLAB Robotics System Toolbox, plot and verify your DH frame assignment in the base configuration according to the figure using the file plot_manip_frames.m (20 points).
3. Write a MATLAB function using a subfunction in fanuc_m900_fk.m to compute the homogeneous transformation between two adjacent frames from the DH parameters (10 points).
4. Write a MATLAB function in fanuc_m900_fk.m to perform the forward kinematics using DH parameters using the function developed in step 3 (30 points). You should compute the position of each joint and all 5 gripper positions in the base frame.

5. Plot and overlay a stick figure of this manipulator on the DH frames created in step 2 in plot_fk.m (20 points). You should plot the manipulator using the pos array that you computed in fanuc_m900_fk.m. Use the base configuration as:
   $\theta_1 = 0, \theta_2 = \frac{\pi}{4}, \theta_3 = -\frac{\pi}{3}, \theta_4 = 0, \theta_5 = \frac{\pi}{4}, \theta_6 = 0.$
   These values are already present in fk_lab.m. Also, plot and overlay the stick figure at some other configuration of your choice. (15 points)

6. Write a MATLAB function in compare.m to compute the error in 3D position of the gripper frame ($o_6$) between the value that we obtain from Robotics System Toolbox and the value that you compute with your own implementation. (5 points)

First part has to be done manually on a piece of paper. Make sure you choose the direction of the base frame ($O_0$) as shown in the figure. Other parts are supposed to be completed in a MATLAB environment.
**Make sure you have latest version of MATLAB installed on your system (R2017a)**
You are provided with five MATLAB files for completing this section:

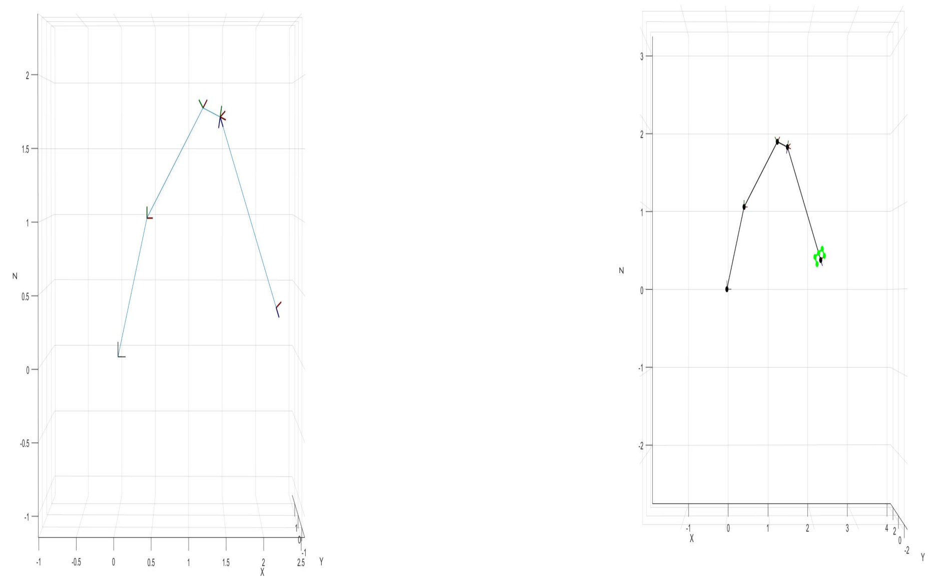
- **fk_lab.m**: This is the main script, it will call the rest of the functions you write. You should change the $\theta$ parameters in the first section of this file to obtain different configurations of the manipulator. You need not change anything else in this file.

- **plot_manip_frames.m**: This function should plot the frames that you have assigned using the Robotics System Toolbox. The function essentially helps you verify your DH parameter table and DH frame assignment – whether they correspond to each other. Your task is to fill the code in this file using functions from Robotics System toolbox. The comments in the file will guide you with the necessary instructions. Check the resources section for useful links on documentation on Robotics System toolbox. These links will help you to complete the function.

- **fanuc_m900_fk.m**: This function takes care of forward kinematics using DH convention. Your job is to complete the implementation in this file. There is a subfunction **compute_dh_matrix.m** in the same file. You can complete this function and use it in your implementation. The function **fanuc_m900_fk.m** returns a **12 x 3 matrix** giving positions of all the joints and the points on the gripper in the world frame. The functions takes in an optional argument to change the width of the gripper.

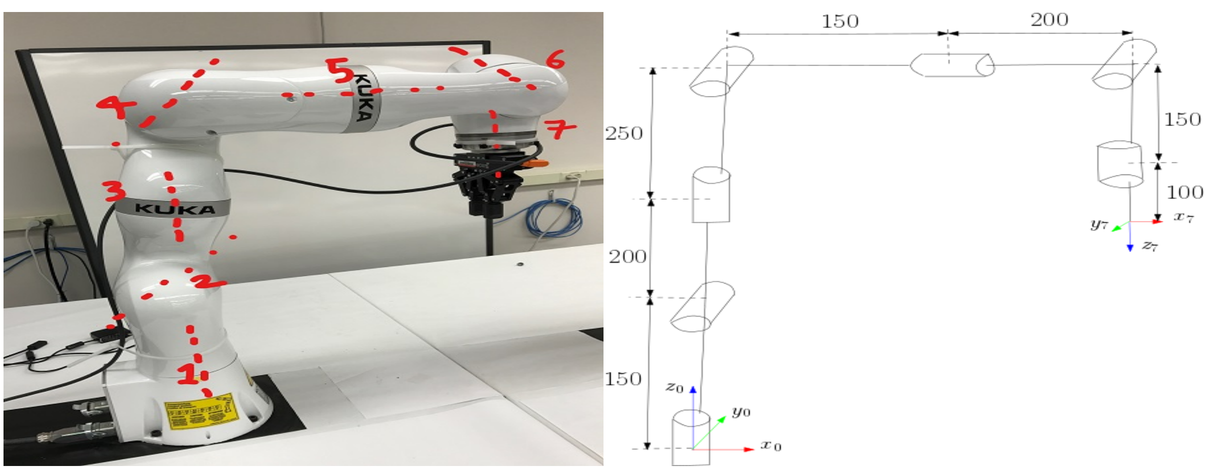
- **plot_fk.m:** In this file your job is to plot a stick figure of the manipulator using positions you obtained from previous functions and overlay this on the DH frames plotted from plot_manip_frames.m. If your forward kinematics are correct, you should see that your stick figure will exactly coincide with the manipulator plotted previously using Robotics system toolbox. You should try to achieve something like in figure 2

- **compare.m:** In this file you will compute the difference between the **position** of the frame $o_6$ as obtained from the Robotics System Toolbox with your computation of position. Check the Resources section for in-built MATLAB functions in Robotics System toolbox. Specifically, we are looking for getTransfom inbuilt function.



(a) Frames and manipulator plotted as per Robotics System toolbox (b) Plot function we write overlayed on top of what we get from Robotics System Toolbox

Figure 2: Expected Outputs




(a) Kuka iiwa manipulator with axis marked (b) Kinematic Diagram of the Kuka iiwa

Figure 3: Kuka iiwa Manipulator

# 3 For Grad Students/ Extra Credit for UnderGrad

Figure 3 shows another question for DH notations with the KUKA iiwa – like the one we have in the RRL robotics lab. For this problem, you are expected to do the following:

1. Assign the frames in the provided kinematic chain and construct the DH table for this manipulator (10 points).

2. Perform the Forward Kinematics for this manipulator modifying the DH notations and the functions you wrote for the previous section. You should write your implementation in **kuka_iiwa_fk.m** Note that this time we will be returning $13 \times 3$ matrix. Modify your plot_fk.m and write the implementation for plotting this manipulator in **plot_fk_extra.m**. You should submit plots at two random configurations (10 points).

3. After you are done with the implementation, you should run **fk_lab_extra.m** which will call all your implementation for this section.

Note that you won't be able to use Robotics System Toolbox for plotting the frames of the KUKA manipulator using DH frames you have assigned. This is because of its unusual design, it is not a standard articulated manipulator. The joint 3 is an additional redundant joint. You will also observe that in the theta parameter column for this manipulator you will invariably have some scalars (like $\pi$ or $\frac{\pi}{2}$). Unfortunately, DH parameter assignment with these kind of values is not supported in Robotics System Toolbox as of now.

# 4 Resources

- https://www.mathworks.com/help/robotics/ug/build-a-robot-step-by-step.html
- https://www.mathworks.com/help/robotics/ref/robotics.rigidbodytree-class.html - Check the example of using DH parameters for plotting at the bottom of this page

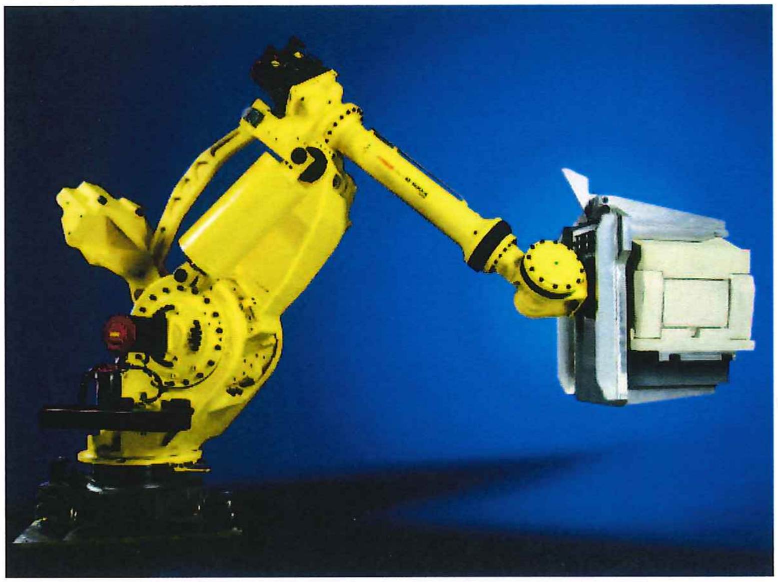
# 5 Submission & Grading

- Handdrawn sketches showing frames assigned to the stick figures according to DH convention.
- Plots of the manipulator at the base configuration and a random configuration of your choice. These plots should show both, the Robotic Toolbox manipulator plot, and your stick figure overlaid on top.
- A .zip file containing all your final code.

# M-900*i*A™ Series

## Basic Description

FANUC Robotics' M-900*i*A series robot is engineered for precision, high-speed/high payload operation, user-friendly setup and maximum reliability supported by our extensive service and parts network. The M-900*i*A series represents our advanced evolution of the company's rugged S-900*i*B series of heavy payload robots. The M-900*i*A series is a six-axis, modular construction, electric servo-driven family of robots designed for a variety of manufacturing and systems processes.



## M-900*i*A Series, the Solution for:

- Material handling
- Machine load/unload
- Heavy duty spot welding
- Large sheet or panel handling
- Glass handling
- Casting operations
- Material removal

## Benefits

- Rugged wrist design performs reliably even in the harshest manufacturing environments.
- Small robot footprint and reduced controller size conserve floor space.
- Slim arm and wrist assemblies minimize interference with system peripherals and allow operation in confined spaces.
- "Best in class" wrist moments and inertia meet a variety of heavy handling challenges.
- Many process attachment points make integration easier.
- Stationary outer arm simplifies hose and cable dressout, prolongs service life.
- Proven, reliable FANUC servo drives provide highest uptime and productivity.
- Invert mount installation is possible on the M-900*i*A/350 & M-900*i*A/260L where space is a big concern.
- Longer maintenance intervals equate to lower operating costs.
- Robust mechanical design reduces down time, increases mean time between failure (MTBF) and minimizes spare part requirements.
- High performance motion yields fast cycle times and high throughput.

## Features

### Mechanical:

- Multiple controller type and mounting capabilities
- 6 axes of motion
- Slim profile design
- RV reducers for all axes
- Process/application cables routed through the arm
- No motors at wrist

### Control:

- Quick change amplifier <5 min.
- Fast boot time <30 sec.
- Standard Ethernet port.
- PCMCIA Software distribution.
- Easy connections to a variety of I/O, including a number of distributed I/O networks.

### Software:

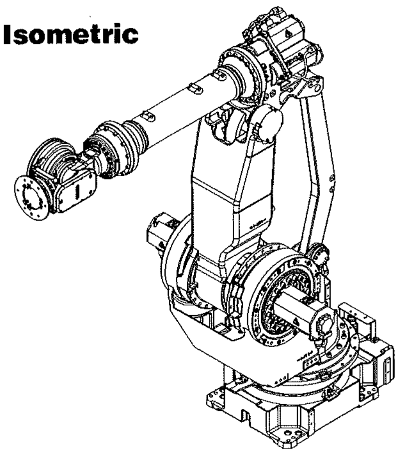
- Process specific software packages for various applications.
- Web-based software tools for remote connectivity, diagnostics and production monitoring.
- Machine vision for robot guidance and inspection.
- *i*Pendant, a color, Internet-ready teach pendant for even easier programming and custom cell user interface design.

## Options

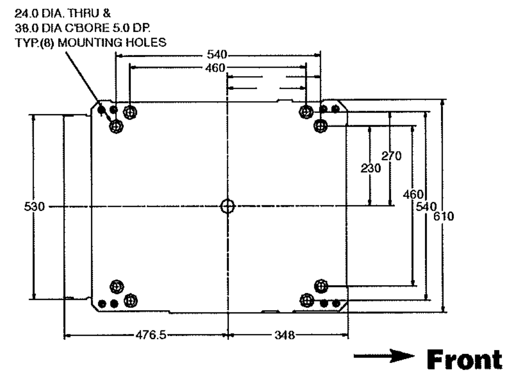
- Enhanced severe dust and liquid protection package with two-part epoxy paint for harsh environments.
- Standard baseplate for quick robot installation.
- Auxiliary axes packages for integration of peripheral servo-controlled devices.
- Adjustable hard stops for J1, J2 and J3.
- Various robot connection cable lengths for flexible cabinet placement and optional track rated cables.
- *i*Pendant is also available with touch screen support.
- Monochrome pendant available.
- Integrated spot welding utilities.
- Electrically-insulated faceplate.

## M-900*i*A/350 & M-900*i*A/260L Dimensions

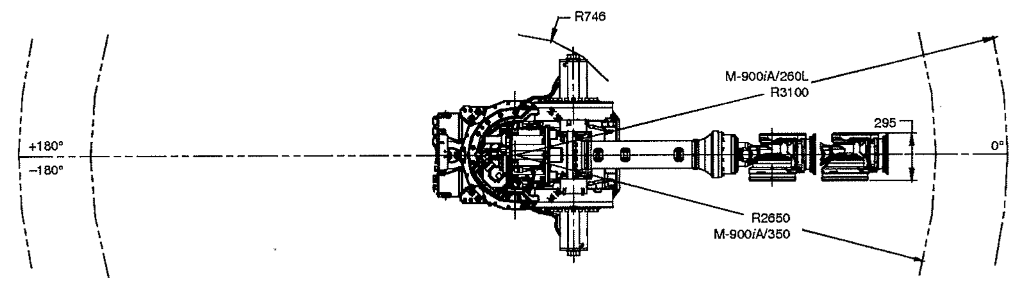
### Isometric

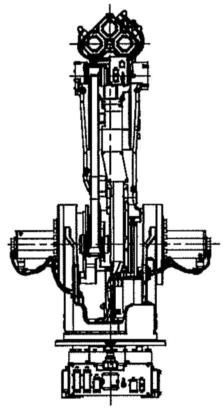


### Footprint

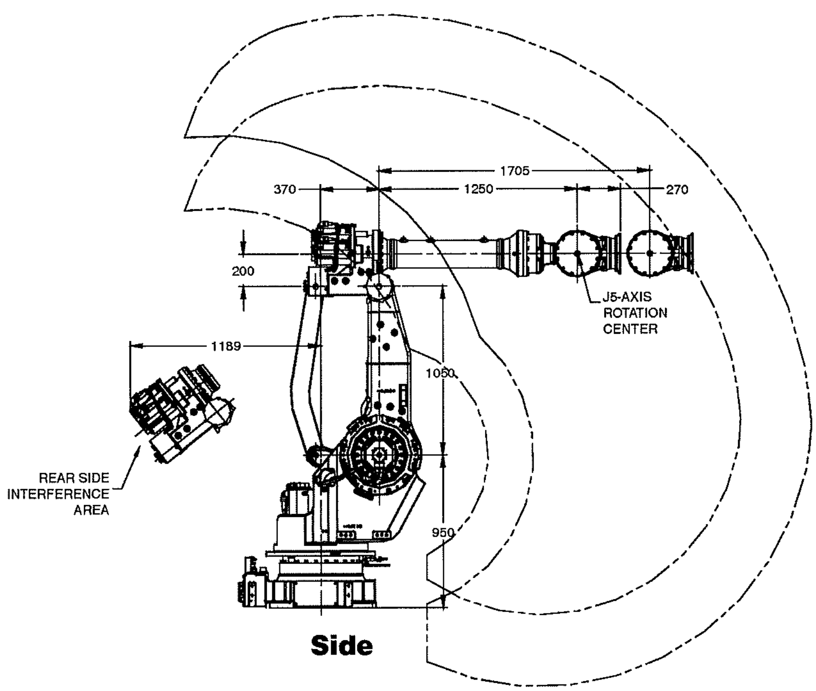



### Top

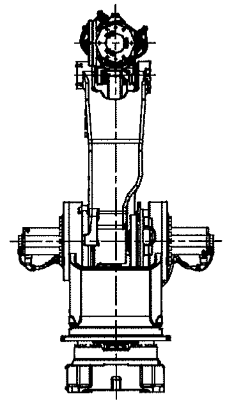


**Back**

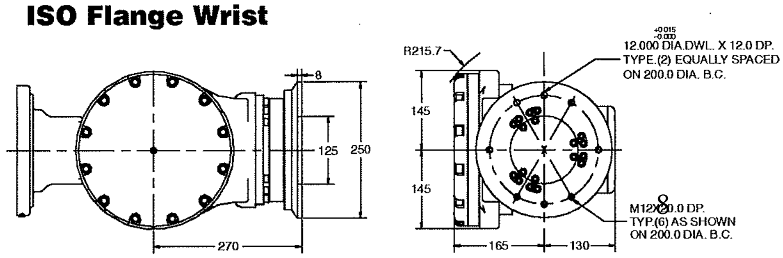



**Side**



**Front**

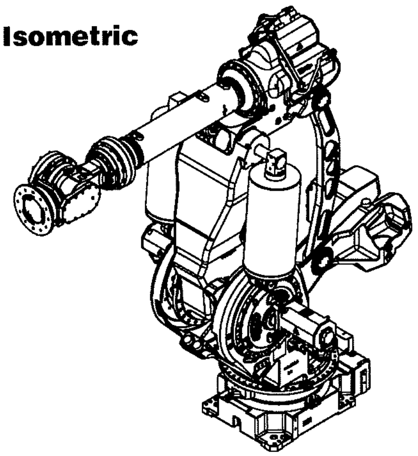
### ISO Flange Wrist



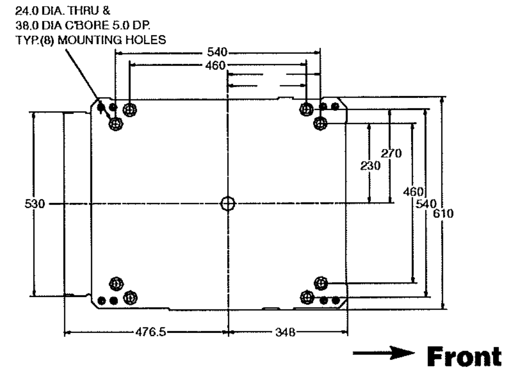

**Note:** Dimensions are shown in millimeters.
Detailed CAD data are available upon request.

# M-900*i*A/600 and 700kg Option Dimensions

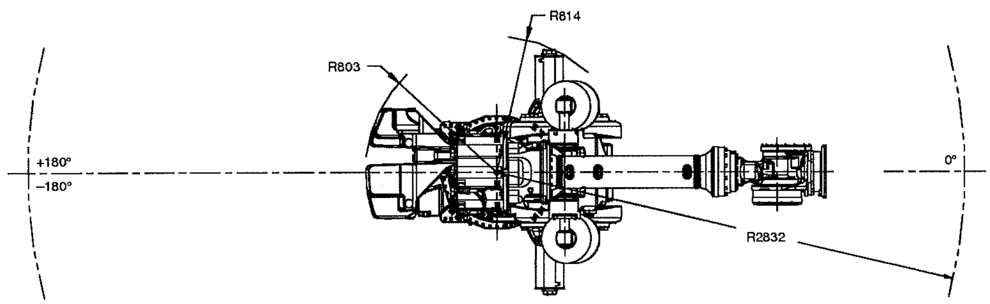
## Isometric

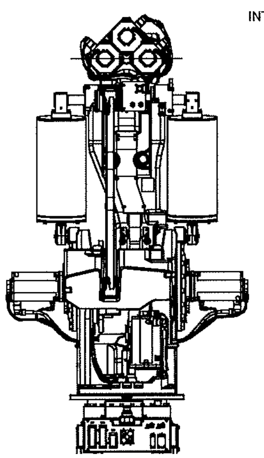


## Footprint

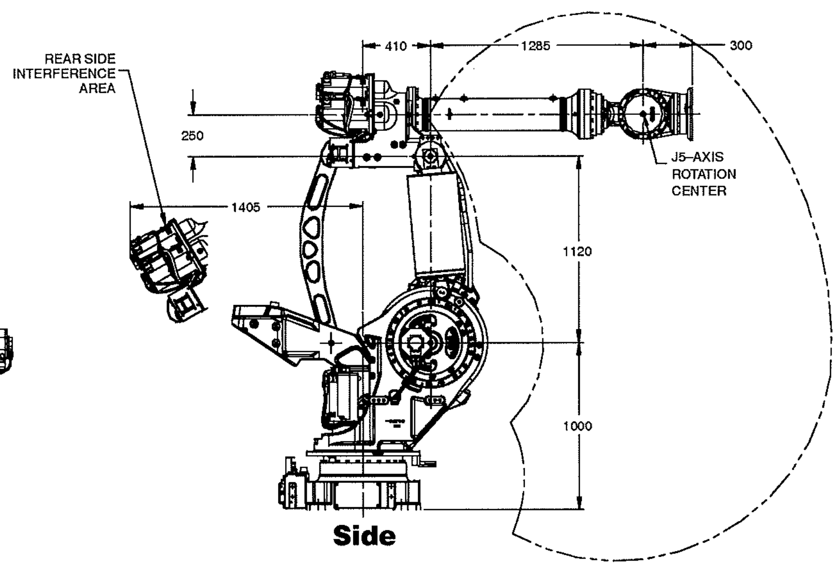



## Top

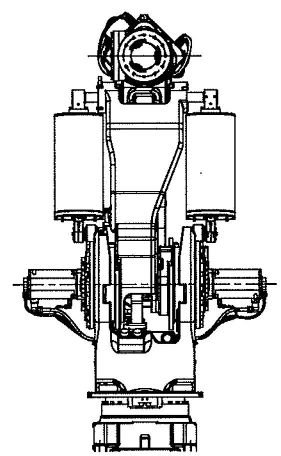


**Back**

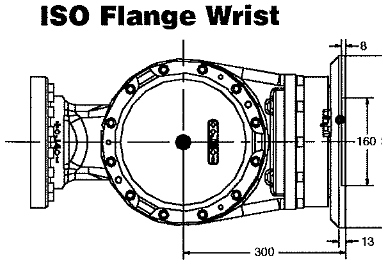


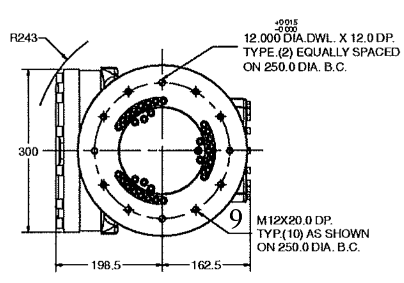

**Side**



**Front**

## ISO Flange Wrist



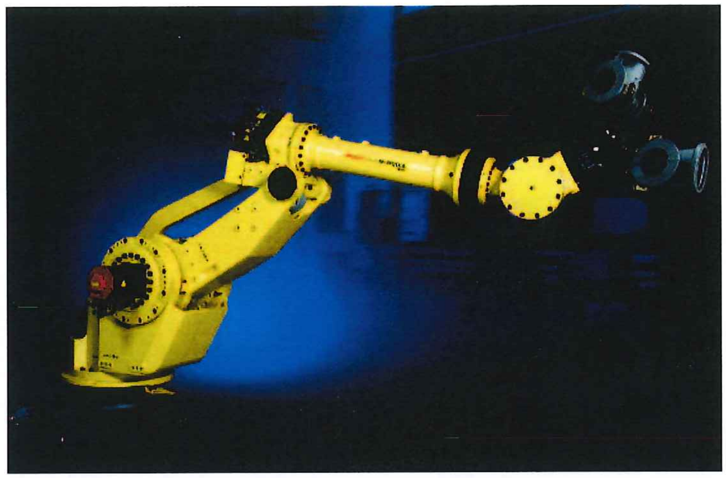




**Note:** Dimensions are shown in millimeters.
Detailed CAD data are available upon request.

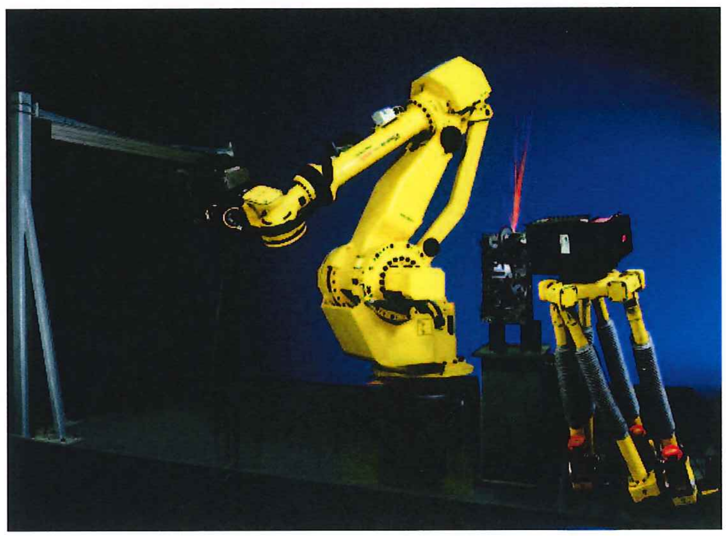
## M-900*i*A Series Specifications

| Items | | /350 | /260L | /600 |
|---|---|---|---|---|
| Axes | | 6 | 6 | 6 |
| Payload - Wrist (kg) | | 350 | 260 | 600/700kg (option) |
| - J3 Arm (kg) | | 25 | 25 | 25 |
| - J2 Base (kg) | | 550 | 550 | 550 |
| Reach (mm) | | 2650 | 3100 | 2832 |
| Repeatability (mm) | | ±0.3 | ±0.3 | ±0.4 |
| Interference radius (mm) | | 746 | 746 | 814 |
| Motion range (degrees) | J1 | 360 | 360 | 360 |
| | J2 | 150 | 150 | 154 |
| | J3 | 223 | 211 | 160 |
| | J4 | 720 | 720 | 720 |
| | J5 | 250 | 250 | 244 |
| | J6 | 720 | 720 | 720 |
| Motion speed (degrees/s) | J1 | 100 | 100 | 80 |
| | J2 | 95 | 105 | 80 |
| | J3 | 95 | 95 | 80 |
| | J4 | 105 | 120 | 100 |
| | J5 | 105 | 120 | 100 |
| | J6 | 170 | 200 | 160 |
| Wrist moment (kgf•m) | J4 | 200 | 170 | 345 |
| | J5 | 200 | 170 | 345 |
| | J6 | 91 | 73 | 176 |
| Wrist inertia(1) (kgf•cm•s$^2$ by axis) | J4 | 2400/3996 | 1920/3200 | 5204/11200 (option) |
| | J5 | 2400/3996 | 1920/3200 | 5204/11200 (option) |
| | J6 | 1600/3600 | 1200/2300 | 3265/4532 (option) |
| Mechanical brakes | | All axes | All axes | All axes |
| Mechanical weight (kg) | | 1720 | 1800 | 2800 |
| Mounting method(2) | | Floor, ceiling angle & wall | Floor, ceilng angle & wall | Floor |
| Installation environment: | | | | |
| Ambient temperature °C | | 0 to 45 | | |
| Humidity | | Normally: 75% or less<br>Short term (within a month): 95% or less<br>No condensation<br>(No dew or frost allowed) | | |
| Vibration (m/s$^2$) | | 4.9 or less (0.5G or less) | | |
| IP Rating(s) | | Wrist & J3 arm IP67, rest IP54 (IP66 optional) | | |

**Notes:**
1) Allowable load inertia at wrist can be switched by software parameters.
2) Motion range will be derated for angle and wall mount.



**Cast iron valve body handling with M-900*i*A/350kg robot.**



**Engine block handling and deflashing with Intelligent M-900*i*A/350kg and F-200*i*B robots.**

**Sand core package handling with M-900*i*A/600kg.**


**FANUC Robotics**

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