Industrial Robot Programming

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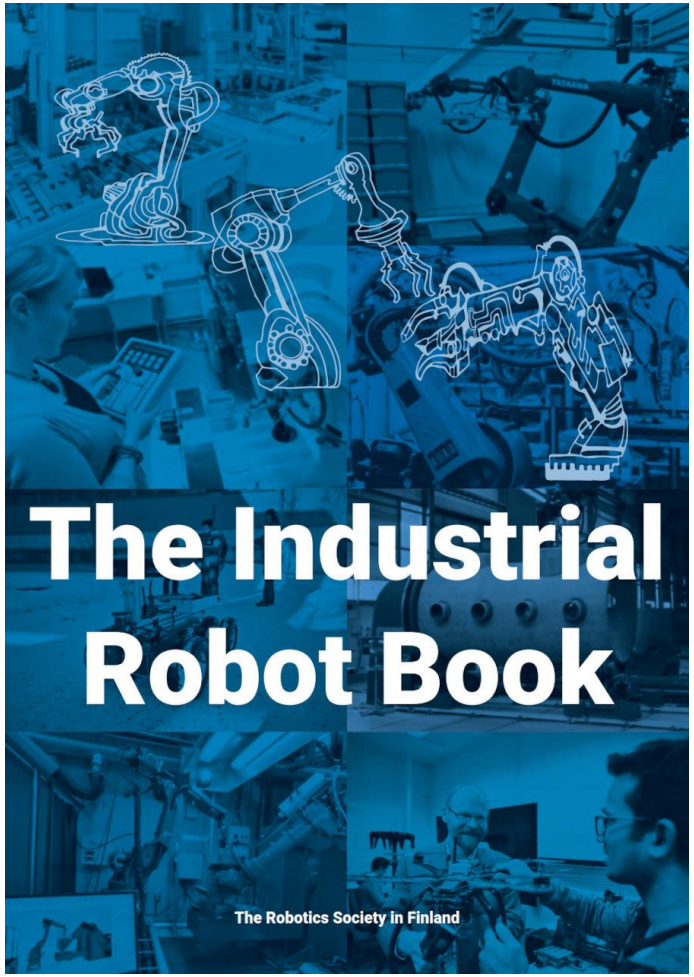
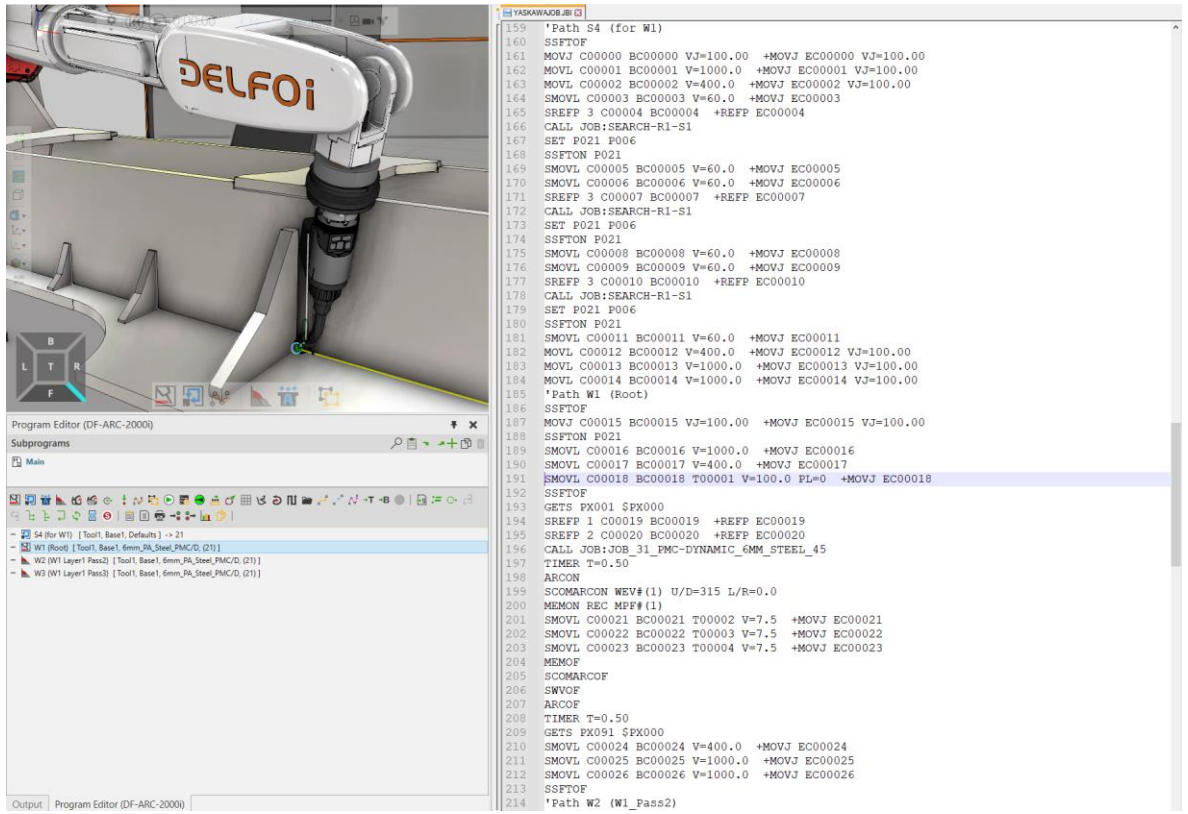
The Industrial Robot Book

- Lecture material is based on the content of the book
  - Chapter 5 – Industrial Robots
  - Chapter 11 – Robot programming
  - Chapter 12 – Simulation and offline programming
- You can buy the book from ellibs online shop or loan it from the university library
  - ISBN 978-952-65329-1-2 (EPUB)
  - ISBN 978-952-65329-2-9 (PDF)



Main tasks of robot programming

- How robot moves?
  - Sequence of operations
  - Motion paths
- How robot communicates?
  - Communication with external devices
- How robot operates in case of errors?
  - Interrupts and error recovery



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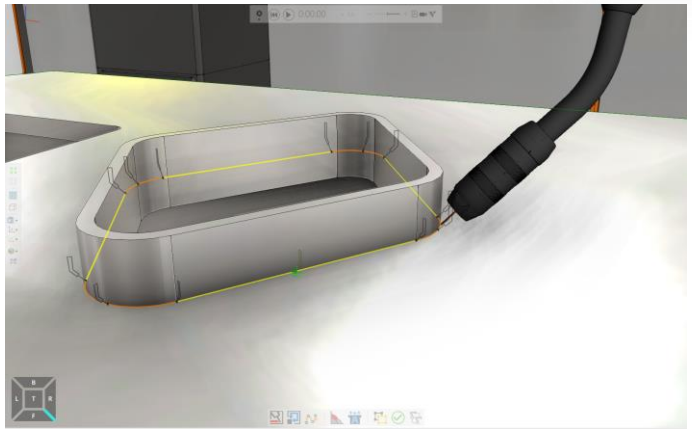
Programming methods

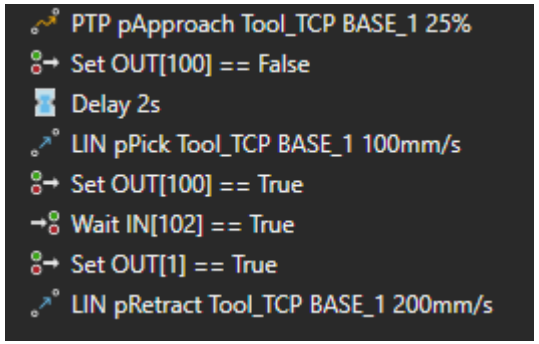
- Programming by guiding
  - Robot's arm and tool are manually moved to the desired position
  - This method has become prevalent with the introduction of collaborative robots and force control
- Teaching
  - Robot's arm and tool are positioned using a hand controller
  - This approach is suitable for programming “simple applications”
- Offline programming
  - Robots are programmed entirely using a computer outside of production
  - Programming can be text-based and/or model-based programming
  - This method is particularly suited for programming “complex applications”
  - It enables programming without interrupting production



Programming languages

- Each robot brand has its own programming language
- The structures of commands and naming conventions used in programming vary between robot brands, but the fundamental principles of programming remain the same
- Programming is based on traditional programming languages like Python and C++, which support mathematical and logical operations
- Programming can utilize either brand-specific software or generic software

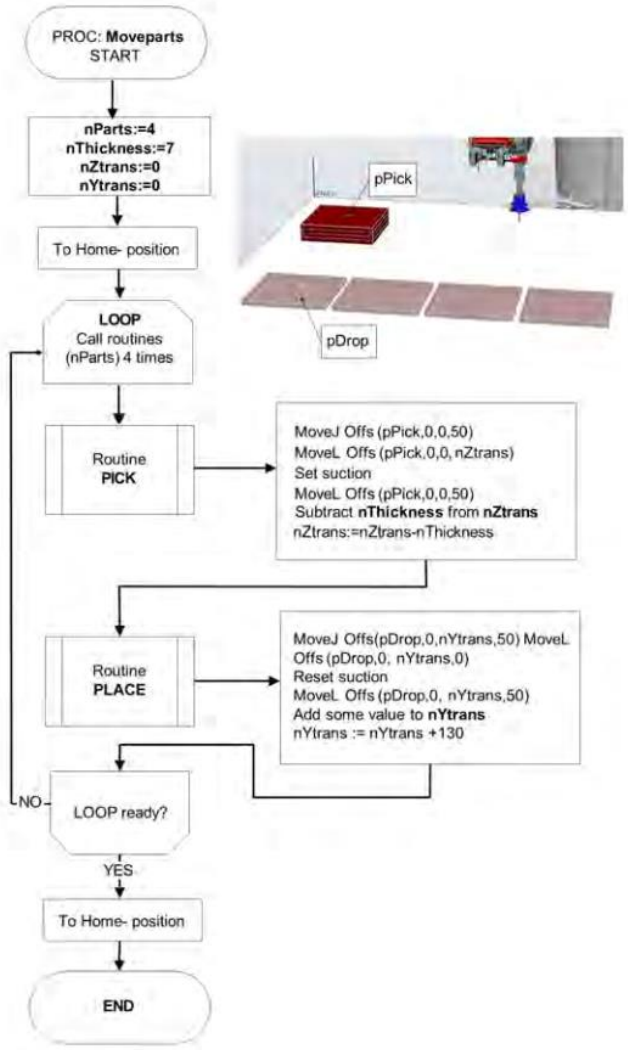
```
PROC main()
    MoveJ pHome,v1000,fine,Pen_TCP\WObj:=wobj0;
    TPErase;
    TPWrite "";
    WHILE TRUE DO
        TPReadFK answer, "Select the product to be manufactured:",
            "Cylinder", "Circle", "Quit", stEmpty, stEmpty;
        IF answer = 1 THEN
            size_determination answer;
        ELSEIF answer = 2 THEN
            size_determination answer;
        ELSE
            TPErase;
            quit;
        ENDIF
        MoveJ pHome,v1000,fine,Pen_TCP\WObj:=wobj0;
        TPErase;
        WaitTime 1;
    ENDWHILE
ENDPROC
```




```
   5:  !Check at HOME
   6:  IF DO[101:HOME Signal]=ON,
    :  JMP LBL[10]
  7:J  P[2:Start] 10% CNT100
   8:  LBL[1]
   9:  R[6:User Input]=0
  10:  CALL LISTMENU(2,6)
  11:  SELECT R[6:User Input]=1,
    :  JMP LBL[3]
  12:        =2,JMP LBL[5]
  13:        ELSE,JMP LBL[2]
```

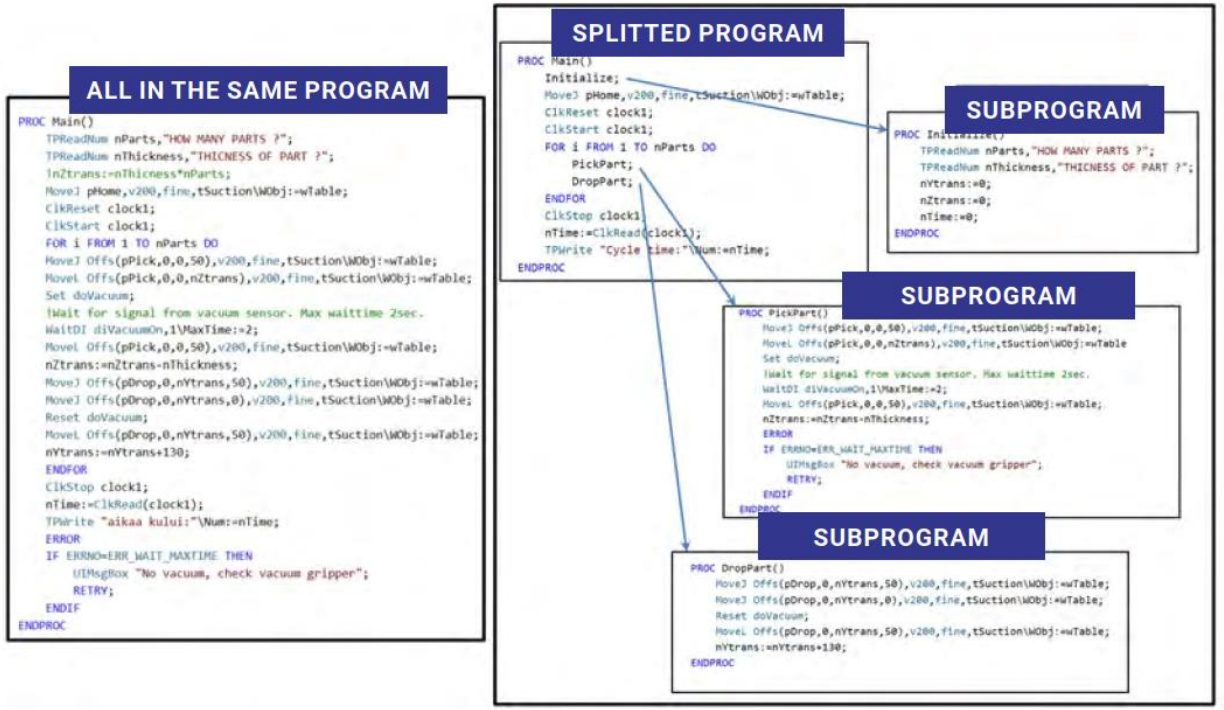
Stages of programming

- Start with process description
  - What should the program do? What are the requirements? What is the workflow?
- Programming the robot
  - Programming principles/guidelines
  - Preliminary reach and collision analysis
  - Definition of variables and other programmable components, such as tool center points, user coordinate systems, signals, etc.
  - Ensure the functionality of selected tool center points and user coordinate systems
  - Sequence of operations and program structure
  - Programming motion commands and other instructions
  - Define background tasks, error handling, and communication
  - Program testing, calibration, and commissioning
- Finally remember the documentation, including etc.
  - Program description
  - Author, date, version
  - Naming of points, variables, signals, TCPs, etc.
  - Commenting the program for better understanding by others
  - Detailed documentation of error handling
  - Listing and documenting peripheral devices and signals



Program structure

- Robot's work program should consist of a main program and subprograms
- Main program should be clear and simple, describe robot's primary tasks, and define the workflow
- Subprograms should contain the functionalities for the specific robot's work tasks
- Program structure should utilize modularity and parameterization whenever possible
  - Reusable subprograms support modularity and eliminate unnecessary reprogramming
    - E.g. standardized programs for tool change
  - Parameterized subprograms improve program reusability by allowing their parameters to be changed dynamically
    - E.g. producing similar but differently sized products using the same program



Robot commands

- A command (or instruction) defines a task that is executed when the command is carried out, such as
  - Moving the robot's arm
  - Turning the robot’s output on/off
  - Waiting for external sensor data
  - Modifying the value of a variable
  - Jumping within the program
- Commands consist of the command name and various definable arguments
  - The command name specifies the primary task, while the arguments provide specific characteristics
  - An argument can be either mandatory or optional, with optional arguments being disregarded if not needed

Basic commands for Industrial robots

- Motion commands
- Program flow commands
- Read and write commands for variables and registers
- Communication commands for external devices
- Error handling commands
- Application-specific commands

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Motion commands

```
MoveJ pPoiminta,v100,z50,tTarrain32\WObj:=wTyopoyta1;
```

Motion Type | Target Point | Speed | Area | Tool (TCP) | (User) Coordinate System

- **Motion type**: Defines the type of movement between points
- **Point**: Defines the position, orientation and configuration of the target point
- **Motion speed**: Defines the movement speed of the tool center point (TCP)
- **Approach data**: Defines how close to a point the TCP moves when passing through it
- **Tool**: Defines the tool center point used for positioning
- **Coordinate system**: Defines the coordinate system in which the target point is placed

```
J  P[2:Start] 10% CNT100
```

```
LIN pRetract Tool_TCP BASE_1 200mm/s
```


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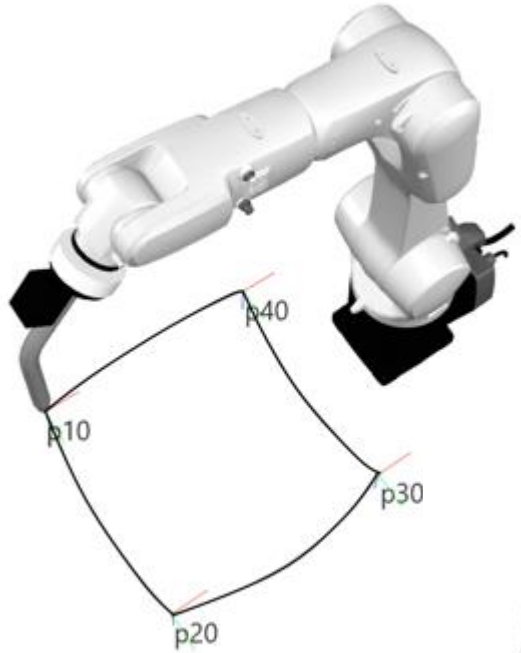
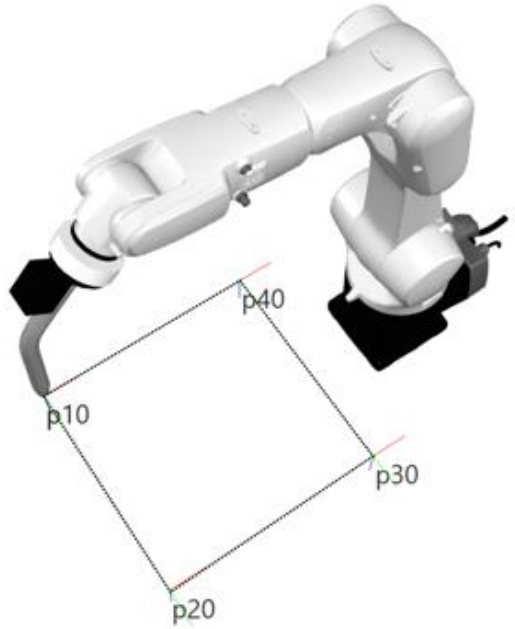
Motion types

- Joint motion
  - The "easiest" way for the robot to achieve positioning
  - Typically the "fastest" type of motion
  - "Undefined" path to the target point
  - Suitable for movements where precise trajectory tracking is not critical
- Linear motion
  - The "most laborious" way for the robot to achieve positioning
  - Typically the "most precise" type of motion
  - Moving along a linear path to the target point
  - Suitable for movements where precise trajectory tracking is critical



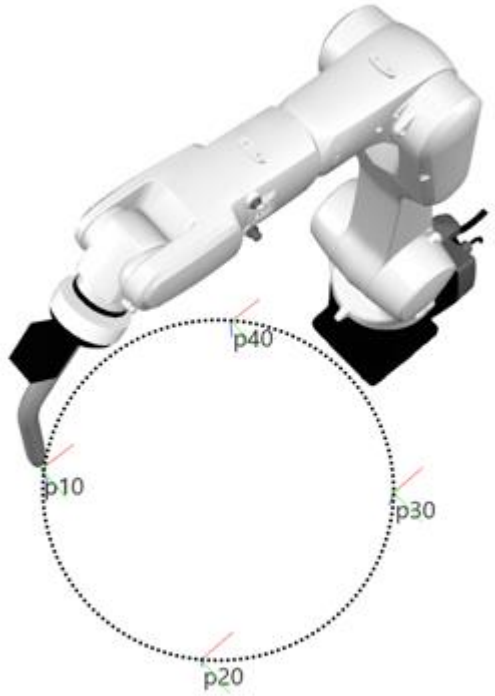
Joint motion



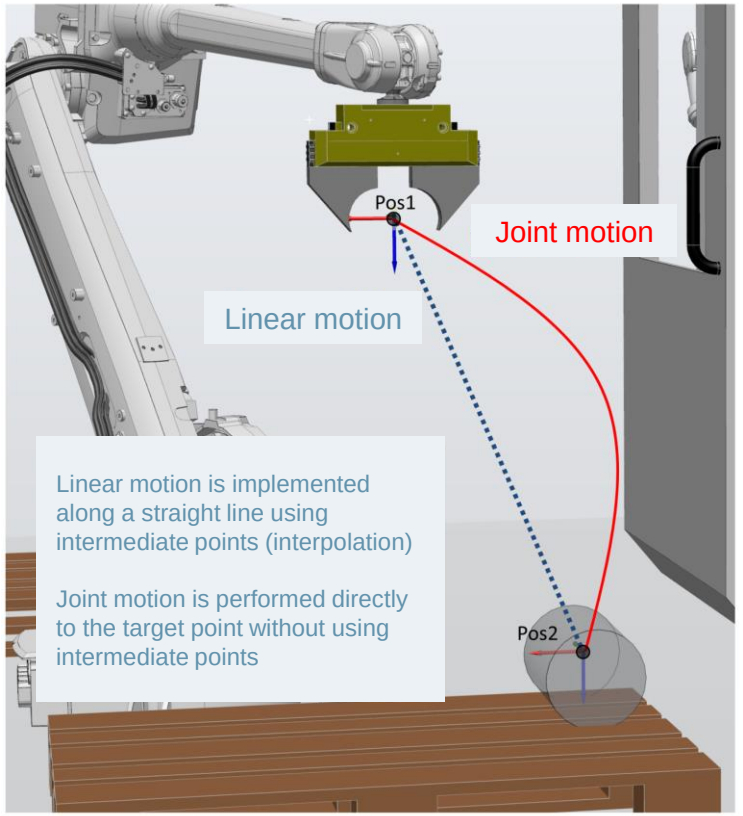
Linear motion

Motion types

- Circular motion
  - Arc movement through a via point to the endpoint
  - Implemented with two positioning points
    - Via point
    - End point
  - Typically, a complete circle motion consists of two circular motion commands
- Suitable motion type is chosen on a case-by-case basis

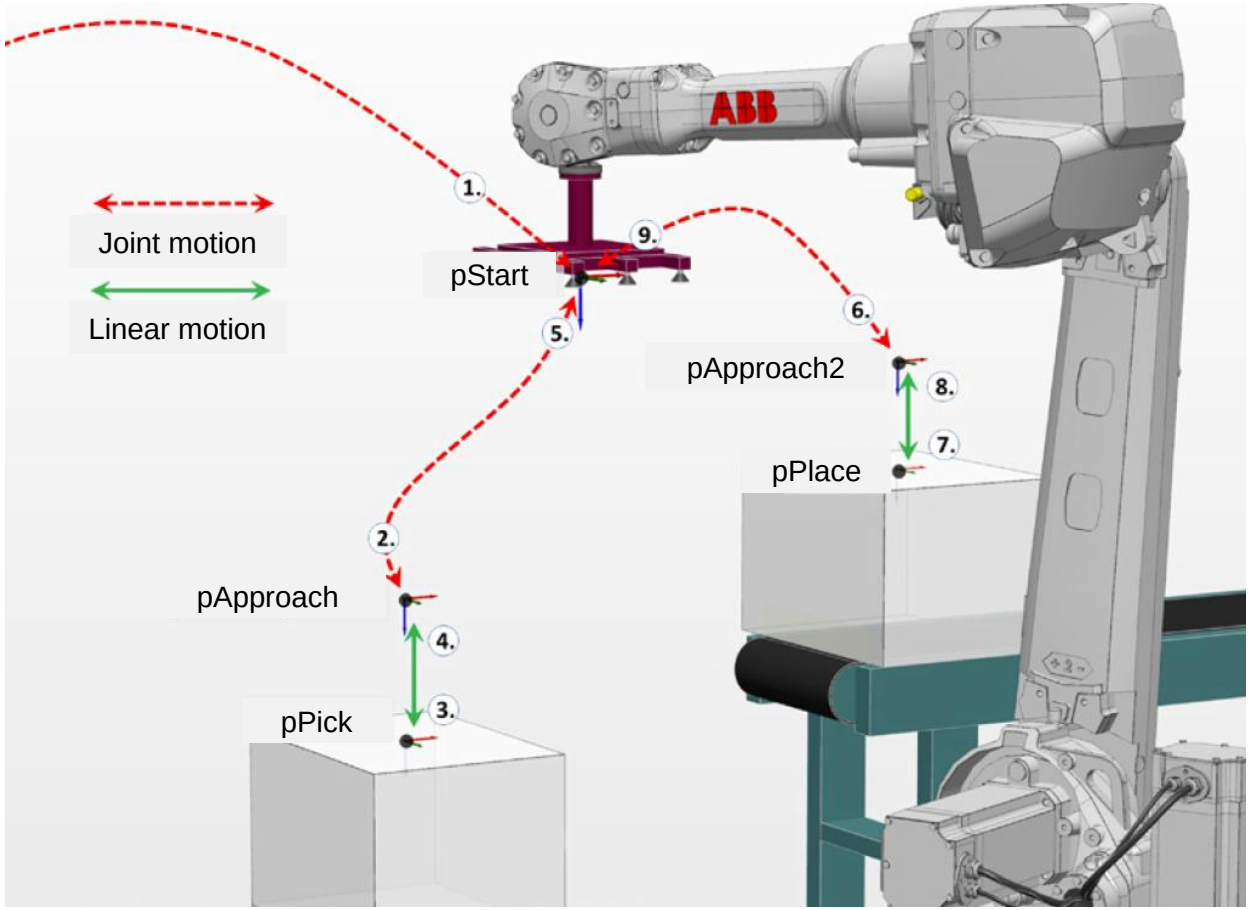


Circular motion



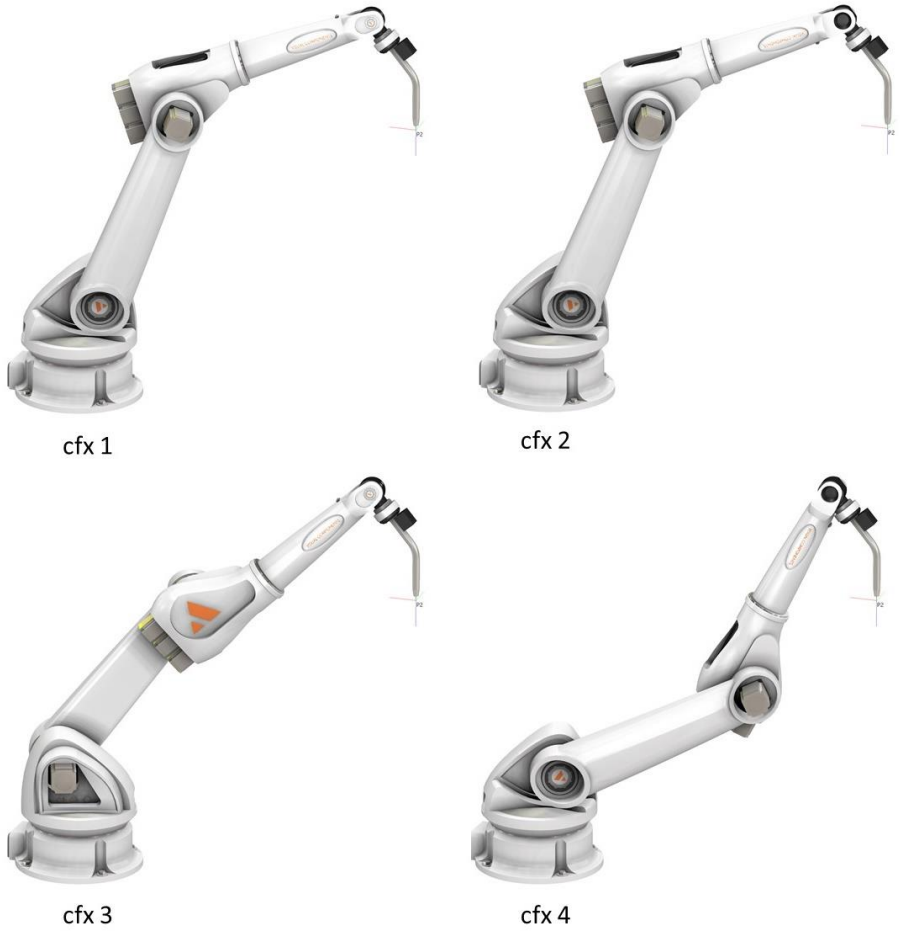
Points

- The location and orientation of the robot's tool center point is relative to the selected coordinate system, including information about the joint configuration
- Motion commands and target points along the robot's trajectory generally follow the same pattern regardless of the application, such as welding, painting, or assembly
  - 1. Start point
  - 2. Approach point
  - 3. Target point(s)
  - 4. Retract point
  - 5. Return to start point
- When defining target points, it is advisable to
  - Use a consistent naming convention
    - E.g., p10, p20, or pPick, pPlace
  - Define target points in the user coordinate system to make modifications easier later on
  - Manage the number of target points to reduce the number of points that need to be maintained and programmed
    - Utilize offset commands when defining approach and retract points



Joint configurations

- Single point can be reached with multiple joint configurations
  - In practice, different poses of the robot's arm can achieve the same target point's location and orientation
  - Therefore, a joint configuration should be defined for each target point in addition to its location and orientation
- In cases of joint configuration errors, the robot may not reach the target point with the given joint configuration
  - This could be due to a significant change in joint configurations between separate target points
- To avoid joint configuration errors
  - Minimize joint configuration changes along the motion paths
  - Avoid large changes in joint configurations when switching between points
  - Avoid joint configurations where the robot's joints are at the extremes of their motion ranges



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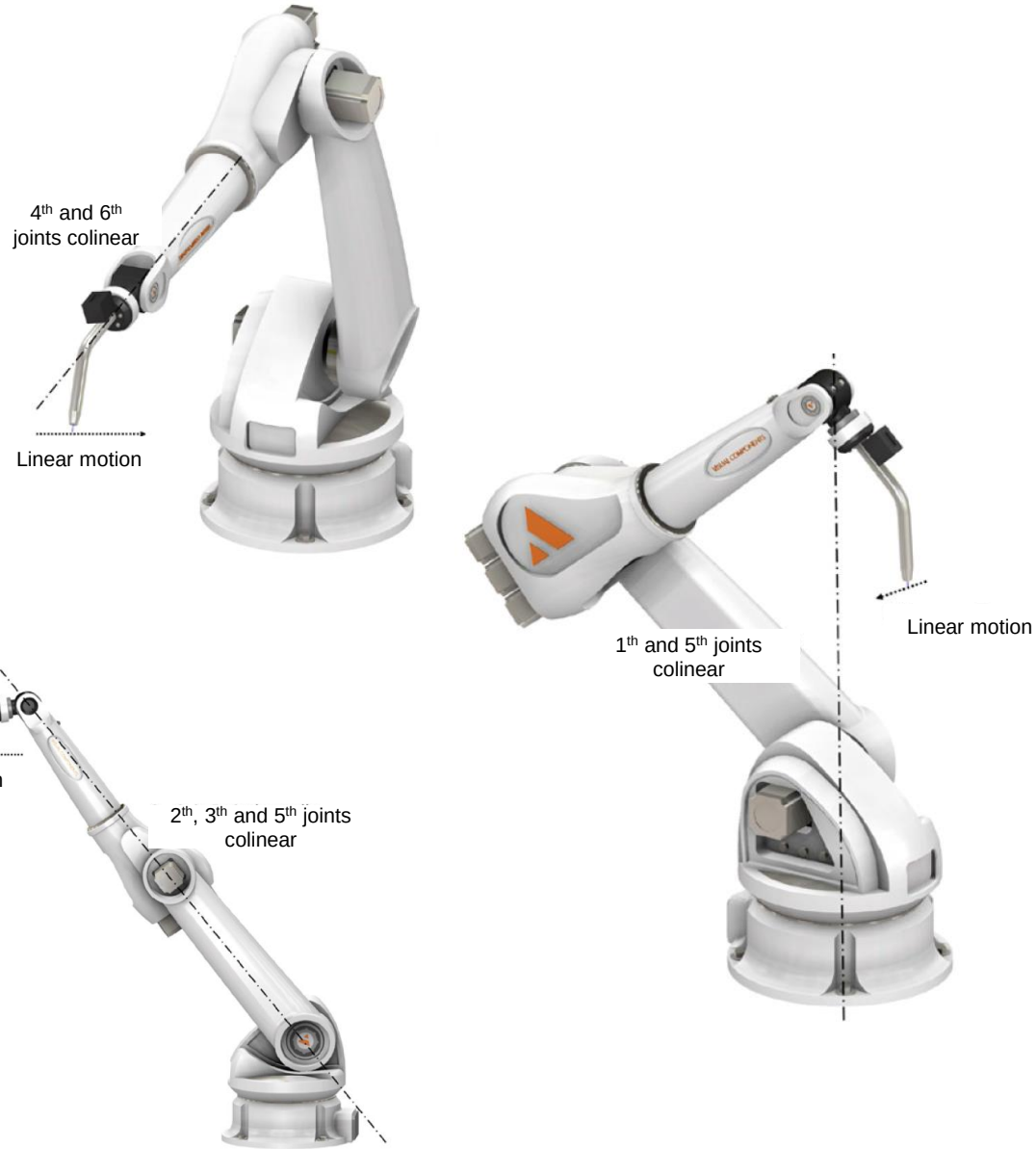
Singularity

- Singularity errors are related to situations where the robot attempts to maintain the tool point's orientation and trajectory throughout its entire movement
- In certain cases, the robot's ability to move the tool point at the selected speed and orientation can be lost, leading to uncontrolled motions and speeds
- These situations occur when
  - Two of the robot's joints align in the same direction (colinear)
    - Causing the joint angle velocities to reach infinite values
  - Two of the robot's joints are concentric
    - Resulting in a loss of degrees of freedom in the motion
- These scenarios are referred to as singularity points, which can be categorized into three types
  - Wrist singularity
  - Elbow singularity
  - Shoulder singularity



Singularity

- Typically, robot stops at the point of a singularity
- However, near singularity points, it is possible to allow the robot to deviate from its path
  - Bypassing a singularity point
- Joint movements are "singularity-free," as the joints move independently toward their target positions rather than along a predetermined path
- Avoiding singularity errors can be achieved through careful programming and design
  - Avoid programming target points close to singularity points
  - Use intermediate points if target points are far apart
  - Utilize joint movements whenever possible to ensure controlled transitions into and out of the manufacturing process
  - In tool design, avoid setting the fifth axis at a 0° position → The wrist should be slightly tilted
- Some robot brands have special commands to handle singularities and joint configuration errors
  - Special commands define the robot's behavior in such situations

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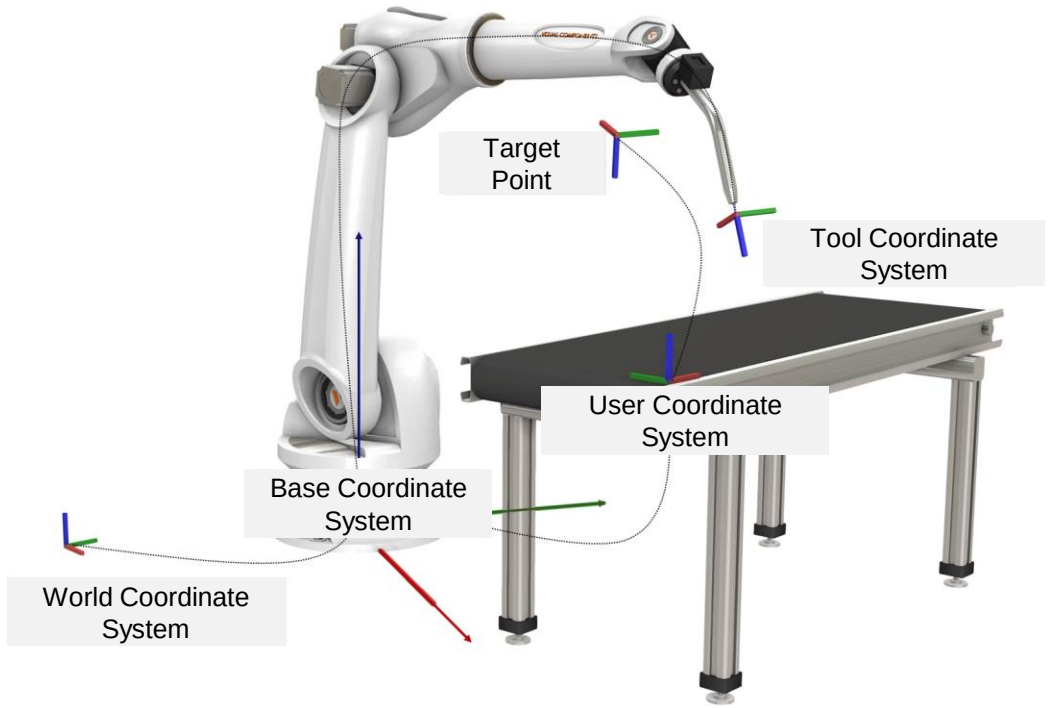
Coordinate systems

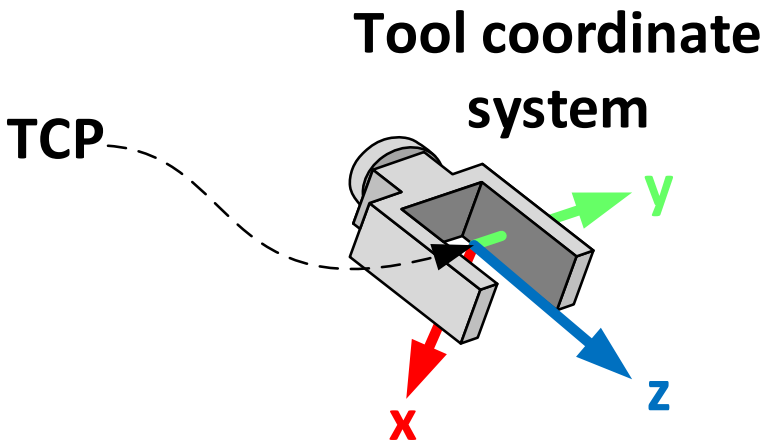
- Coordinate systems are used to represent the locations and orientations of points in a three-dimensional environment
- Various coordinate systems of robots are interconnected
- Tool and user coordinate systems are linked to the base coordinate system, which determines the placements and movements of the robot
- Target points are always stored in the selected coordinate system
  - If a user coordinate system has not been defined, it is replaced by the base coordinate system
- User coordinate system defines a coordinate system specifically intended for the robot's working area
  - It indicates both the location of the origin (0, 0, 0) and the angular offsets around the X, Y, and Z axes in the base coordinate system
  - It is possible to define multiple user coordinate systems for a robot, so it is essential to choose which one to use
  - Defining positioning points in the correct user coordinate system facilitates the modifications and transfers of programs later on

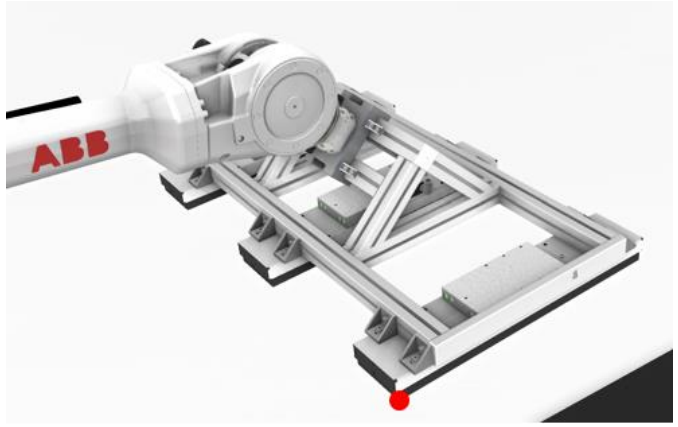


Tool Center Point

- Robot's positioning and movements are linked to the tool center point and the tool's orientation

  → Tool coordinate system
- Tool Center Point (TCP) is the point to which all robot positioning is related
- It is possible to define multiple tool coordinate systems for a robot, so it is essential to choose which one to use
  - If a user coordinate system has not been defined, it is replaced by the default tool coordinate system





Speed

- Speed is specified based on the type of movement
  - **Joint movements:** Percentage of the maximum rotational speed of the robot's axes
  - **Linear and circular movements:** Distance traveled by the tool point in a specific time (e.g., mm/s)
- Speed is set on a case-by-case basis, for example
  - Lower speeds for pick and place points
  - Higher speeds for approach and departure points
- Move command’s speed setting can be overridden, for example
  - With a separate command
  - Using the robot’s hand controller

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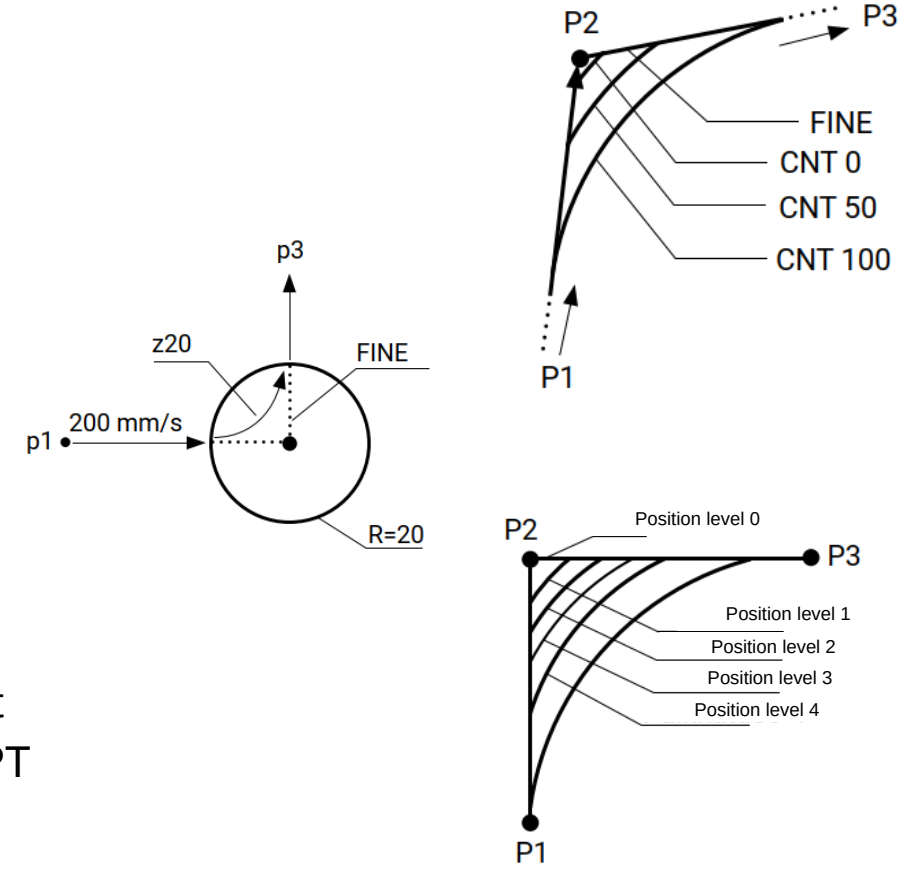
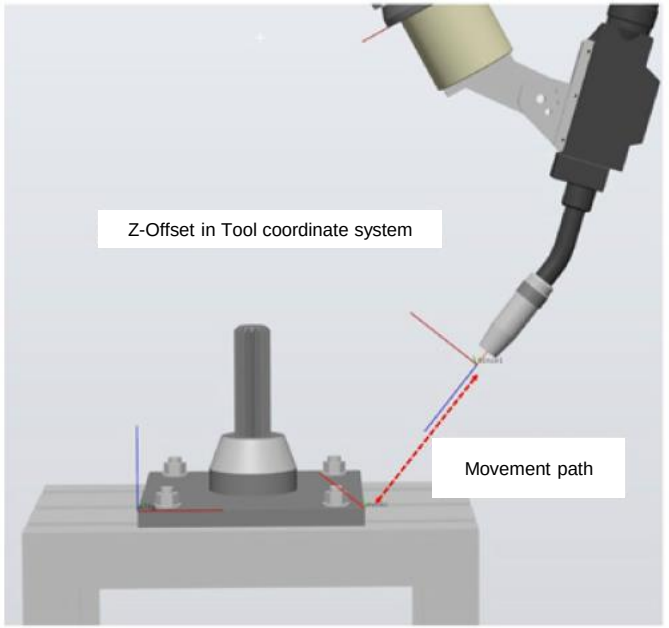
Approach data

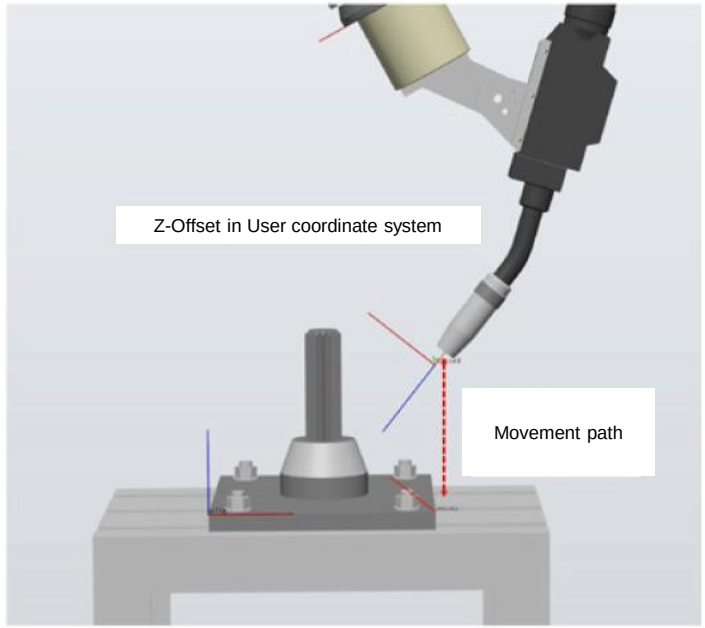
- Zone accuracy defines how accurately target point is reached
  - How much deviation is allowed in the robot's motion path
  - Useful for optimizing programs
- Zone accuracy is defined differently by each robot brand
- The Fine value is used to achieve precise positioning
  - Target point is reached accurately
  - Robot stops at the target point before moving to the next point
  - Fine values are used, e.g. at pick and place points
- Brand-specific values are used for path smoothing
  - Target point is not reached accurately
  - Robot does not stop at the target point before moving to the next point
  - For example: ABB’s Zone value, Fanuc's CNT value, and Yaskawa's PT value
  - Path smoothing can be used, e.g. at approach and departure points



Other arguments for motion commands

- Vary by robot brand
- Offset functions, i.e., position data translations
  - The robot's target point is shifted relative to the original point
  - Adds specified values to the original target point for location (X, Y, Z) and/or orientation (Rx, Ry, Rz)
  - Implemented in two ways:
    - Offset along tool coordinate system
    - Offset along user coordinate system





Other arguments for motion commands

- Acceleration/Deceleration
  - Adjusts the rate of change of the speed specified in the motion command when departing from or reaching target points
  - Control of acceleration/deceleration is necessary, e.g. when handling a workpiece
    - High acceleration/deceleration values may cause the workpiece to detach from the gripper

- Payload
  - Specifies the mass, center of mass, and any moments of the robot tool and workpiece
    - Important for motion control and accuracy
  - Different payloads apply when the gripper is empty versus when handling a workpiece
    - Incorrect payload settings may cause positioning inaccuracies

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Variables

- Variables in programming refer to a named, symbolic data storage that allows information to be retrieved (read) and stored (written)
- A variable has a symbolic name (identifier), a value, and a scope
  - Symbolic name is referenced during programming
  - Value can be changed during program execution
    - **Exception:** Constant variables, whose values cannot be changed
  - Scope defines the area within the program where the variable can be used
- Different types of variables exist depending on the robot brand, typically including:
  - Strings
  - Numeric variables (integer, float)
  - Boolean (true/false)
- Variables enables dynamic robot programming
  - Parametric programming
- Registers enable storing and reading values of variables and other programming components in lists/arrays

```
8   PROC Main()
9       init;
10      MoveAbsJ jHome,v1000,z50,tool0\WObj:=wobj0;
11      !Asking product lenght from operator
12      TPReadNum nProductLenght,"Enter product lenght (mm)";
13      !calculating  x-coordinate of pickpoint = products lenght/2
14      !This value is used in move instructions offset function.
15      nPick_X:=nProductLenght/2;
16
17      WHILE TRUE DO
18          WaitDI diPArtOnPos,1;
19          MoveJ Offs(pPick,nPick_X,0,200),v1000,z50,tSuction\WObj:=wConveyor;
20          MoveL Offs(pPick,nPick_X,0,200),v100,z50,tSuction\WObj:=wConveyor;
21          Set doVacuum;
22          MoveL Offs(pPick,nPick_X,0,200),v300,z50,tSuction\WObj:=wConveyor;
23          MoveAbsJ jHome,v1000,z50,tool0\WObj:=wobj0;
24          DropPart;
25      ENDWHILE
26  ENDPROC
```

The offset value of the picking point depends on the length of the product

Program flow commands

- Programs are rarely executed from start to finish in the written order of commands
  - Various program flow commands are used to control program execution
- **Conditional Statements**
  - Executing a specific part of a program until predefined conditions are met
  - Typically implemented with IF structures
    - IF
    - IF – ELSE
    - IF – ELSE IF – ELSE
- **Loops and Iterative Structures**
  - Repeating a specific part of a program
  - Section of the program can be repeated a set number of times, until a certain condition is met, or indefinitely
  - Various implementation options:
    - **FOR Loop**
      - The number of repetitions can be set as an absolute value, e.g., repeat a part of the program 10 times
    - **WHILE Structure**
      - The number of repetitions is tied to a condition, e.g., repeat until a certain variable changes from false to true
      - It is also possible to define an infinite loop for an indefinite period by setting the condition to "True"

```
PROC main()
    MoveJ pHome,v1000,fine,Pen_TCP\WObj:=wobj0;
    TPErase;
    TPWrite "";
    WHILE TRUE DO
        TPReadFK answer, "Select the product to be manufactured:",
            "Cylinder", "Circle", "Quit", stEmpty, stEmpty;
        IF answer = 1 THEN
            size_determination answer;
        ELSEIF answer = 2 THEN
            size_determination answer;
        ELSE
            TPErase;
            quit;
        ENDIF
        MoveJ pHome,v1000,fine,Pen_TCP\WObj:=wobj0;
        TPErase;
        WaitTime 1;
    ENDWHILE
ENDPROC
```


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Program flow commands

- Program/Function Calls
  - Calling subprograms to execute the functionalities they contain
  - Programs can be called from main programs or from other programs
    - Various parameters can be passed to the subprogram in the function call
  - After the subprogram has been executed, program execution returns to the main program
    - The subprogram can also return values to the main program
- Jump Commands (Jump/Label)
  - Jump commands transfer program execution to a specific location (branch) within the program
    - A jump can be conditional, e.g., jump to line X if the value of a variable is true

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Program flow commands

- Wait Commands
  - Suspend program execution temporarily
  - The duration of the pause can be predetermined or condition-based
    - Predetermined time, e.g., 1 second
    - Condition-based, e.g., waiting until a specific signal state changes to true
  - Delays are often needed in programming, for example, to accommodate pneumatic actuators
- Stop/Pause Commands (Halt/Break/Pause)
  - Designed to stop program execution and allow the program to resume from where it left off when restarted
- Exit/Abort Commands
  - Intended to stop program execution and terminate it without the option to resume from the point of interruption

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Peripheral control commands

- Robots are always part of a production system, making communication with other devices, such as grippers, conveyors, programmable logic controllers (PLCs), and other robot cells, essential
  - Control of production cells can be centralized, for example, using PLCs
  - Various types of bus computing solutions and traditional I/O controls are available to facilitate communication
- Communication between the robot and peripheral devices typically uses I/O control
  - The **Set** command sets a selected output signal to a value of 1
  - The **Reset** command sets a selected output signal to a value of 0
  - The **WaitDI** command waits for a selected input signal to change to either 0 or 1
- Traditional I/O control is the simplest option for controlling the robot's peripheral devices
- If external axes are attached to the robot, e.g. if the robot is mounted on a linear track, their control is integrated into the robot's control system
  - In the case of a linear track, the track's servomotor acts as the robot's "7th axis"

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Error Handling

- Preparing for errors and recovering from errors is one of the most challenging tasks in robot programming
  - In error situations, the program operates differently than usual → Causes challenges
- There are different methods for error handling
  - Safely suspending program execution and/or
  - Recovery actions to recover from the error
- There are various types of errors, such as missing sensor data
- When a predefined error is detected, an error handler is activated
- Different commands can be used in error handling, for example
  - The **WaitDI \ Maxtime** command can identify if a predefined signal does not respond within a specified time, triggering error handling in the program
  - **Error** program blocks can be used to transfer program execution to error handling
  - **Retry**, **Trynext**, and **Return** commands allow retrying the program section after error correction, moving to the next command after error handling, or returning to program execution after error handling
- Not all error situations can be automatically recovered
  - For example, emergency stops and collisions require the operator to perform recovery actions

```
PROC PickPart()
    !Routine for picking part from pile.
    MoveJ Offs(pPick,0,0,50),v200,fine,tSuction\WObj:=wTable;
    MoveL Offs(pPick,0,0,nZtrans),v200,fine,tSuction\WObj:=wTable;
    Set doVacuum;
    !Wait for signal from vacuum sensor. Max waittime 2sec.
    WaitDI diVacuumOn,1\MaxTime:=2;
    MoveL Offs(pPick,0,0,50),v200,fine,tSuction\WObj:=wTable;
    nZtrans:=nZtrans-nThickness;

    ERROR
    IF ERRNO=ERR_WAIT_MAXTIME THEN
        UIMsgBox "No vacuum, check vacuum gripper";
        RETRY;
    ENDIF
ENDPROC
```

If signal is not **1** after 2sec. Then execution jump to ERROR-handler

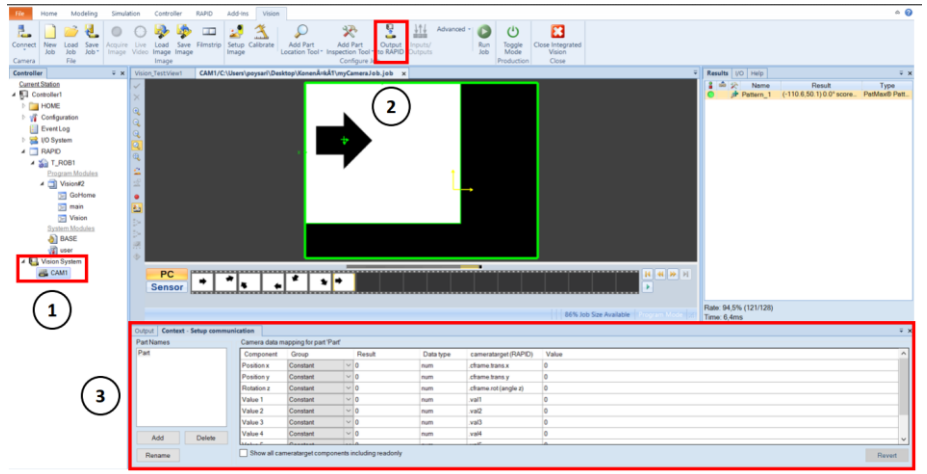
Program execution stops, info text appears to handling unit.

Operator approve error and program jump back and trying again.

Application-specific commands

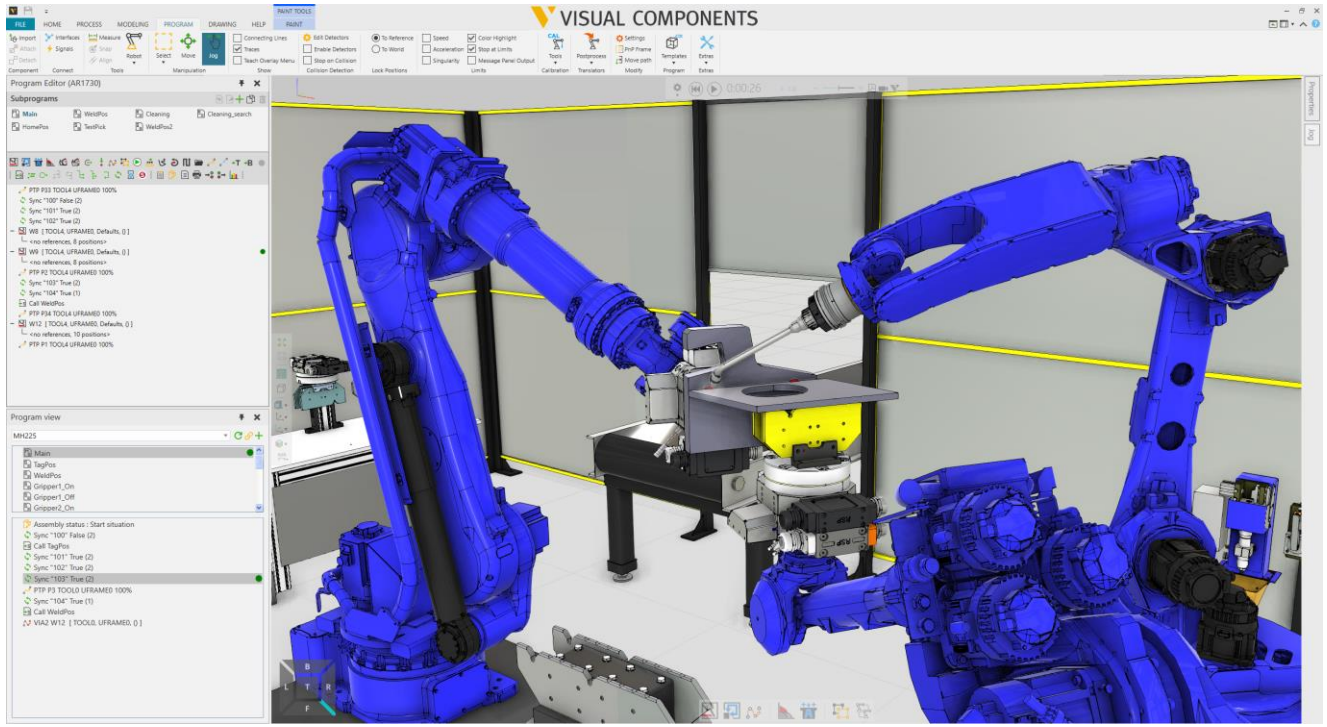
- Welding
- Painting
- 3D printing
- Palletizing
- Polishing
- Deburring
- Machine Vision
- Safety
- Etc.

```
PROC Vision()
  !Laitetaan kamera ohjelmatilaan. Vaihda tarvittaessa kameran nimi.
  CamSetProgramMode CAM1;
  !Lataa tehty konenäköohjelma.Vaihda tarvittaessa kameran nimi.
  CamLoadJob CAM1, myjob;
  !Aseta kamera päälle. Vaihda tarvittaessa kameran nimi.
  CamSetRunMode CAM1;

  !Siirretään robotti joko kuvauspisteeseen (jos kamera kiinnitettynä robottiin) tai sivuun kameran kuvausalueelta.
  MoveJ pCamera,v1000,fine,tool0\WObj:=wobj0;

  !Asetetaan alkuun, että kappaletta ei löytynyt.
  bPartFound:=FALSE;

  !While-silmukalla etsitään kuvaa.
  WHILE bPartFound = FALSE DO
      !Otetaan kameralla kuva. Vaihda tarvittaessa kameran nimi.
      CamReqImage CAM1;
      !Asetetaan muuttuja alustavasti todeksi, jos kuva saadaan otettua.
      bPartFound:=TRUE;
      !Jos ei saada kuvaa 2 sekunnin kuluessa siirrytään
      !virheenkäsittelyyn ja yritetään ottaa kuva uudestaan.
      CamGetResult CAM1, mycameratarget \MaxTime:=2;
  ENDWHILE

  !Siirretään otetusta kuvasta löydetyn kappaleen sijaintitiedot robotin työkoordinaatistoon.
  wCameraSystem2.oframe := mycameratarget.cframe;
```



Programming checklist

- Before Programming
  - Create process description
  - Define/review programming guidelines
  - Conduct preliminary reach and collision analysis
  - Define the workflow and program structure → Modularity and parametrization
  - Define variables and other programmable components, e.g. user and tool coordinate systems
  - Define preliminary communication with peripheral devices and error handling
- During Programming
  - Use correct and tested user and tool coordinate systems
  - Select appropriate motion types, speeds, and zone accuracies
  - Define points carefully
  - Check joint configurations and singularities
  - Add communication with peripheral devices and error handling
  - Program the entire workflow
  - Comment the program
- After Programming
  - Test and optimize the program (simulate if possible)
  - Calibration of robot system (for offline programming)
  - Commissioning
  - Documentation



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