Advanced Vision
Guided Robotics

David Bruce
Engineering Manager
FANUC America Corporation
Traditional Vision vs. Vision based Robot Guidance

- **Traditional Machine Vision**
  - Determine if a product passes or fails
    - Assembly Verification
    - Find Defects
    - Gauging/Metrology

- **Vision Guided Robots or VGR**
  - It all about location,
    - Locate and pick parts
    - Locate and move relative to parts for assembly
    - Locate parts and remove flash or apply epoxy
Robotic System Adaptability

- Basic Premise: Vision Guidance is needed when the part is not always in the same position.
- Vision technology has enabled a variety of robotic applications.
The world is not flat...

- Traditional cameras see a flat world – 2D and flat

- Robots work in the real world and must compensate for a parts position with 6 degrees of freedom using machine vision
Vision Guided Robotics - VGR

• Consider a simple vacuum gripper attached to an industrial robot.
• Now consider a small cylindrical part sitting at some random position & orientation relative to that robot.
Our ultimate goal:

How can vision be used to guide the robot to the position and orientation of a part?
Position Relationships

• Start with a Cartesian coordinate system for rendering position (X,Y,Z)
• \( \mathbf{R} \) is the position of the platter relative to the Room.
• \( \mathbf{T} \) is the position of the table in the Room coordinate system.
• \( \mathbf{P} \) is the position of the platter in the table frame or table coordinate system.
• Now consider the same table where adjacent legs are shorter such that its top is at an angle.
Position Relationships

- **R** would change.
- **T** would change.
- **P** would remain the same as it represents the position of the platter on the table irrespective of the table's position in the room.
Position Relationships

- To fully represent an object in a coordinate system the object’s position and orientation need to be defined.
- The position is represented by 3 elements typically referred to as XYZ which is distance from coordinate system origin along each axis.
- The orientation defines the angle of the object about each axis of the base coordinate system, Yaw, Pitch & Roll or W, P, & R.
- Position and Orientation together are sometimes referred to as the Pose.
Industrial Robots

- Industrial robots come in all shapes and sizes.
- The all are made up of a number of serial linked or parallel linked joints either rotational or translational.
Industrial Robots – Joint Positions

- 6 Axis serial linked industrial robot.
  - J1
  - J2
  - J3
  - J4
  - J5
  - J6

<table>
<thead>
<tr>
<th></th>
<th>J1</th>
<th>J2</th>
<th>J3</th>
<th>J4</th>
<th>J5</th>
<th>J6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-50.000 deg</td>
<td>50.000 deg</td>
<td>-20.000 deg</td>
<td>50.000 deg</td>
<td>50.000 deg</td>
<td>0.000 deg</td>
</tr>
</tbody>
</table>
Industrial Robots – Joint Positions

- 4 Axis parallel linked industrial robot.
  - J1
  - J2
  - J3
  - J4
Industrial Robots- Joint Positions

- 6 Axis serial linked industrial robot with J1 translation axis

- J1
- J2
- J3
- J4
- J5
- J6

<table>
<thead>
<tr>
<th></th>
<th>J1</th>
<th>J2</th>
<th>J3</th>
<th>J4</th>
<th>J5</th>
<th>J6</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>-500.000 mm</td>
<td>15.000 deg</td>
<td>25.000 deg</td>
<td>40.000 deg</td>
<td>50.000 deg</td>
<td>0.000 deg</td>
</tr>
</tbody>
</table>
Industrial Robots – Cartesian Position

- Industrial robots can represent their current position in terms of individual Joint Angles or through kinematic equations also in Cartesian Coordinates.
• All robots have a base coordinate system often referred to as World. All other coordinate systems are defined relative to this base or world frame.
• Most robots follow the right hand rule!
User Frames

- Industrial robots will allow a user to define many sub-worlds referred to as User Frames, Base Frames, Work Objects, etc. These are other coordinate systems whose definition is based on world.

- A user frame definition is the same as a position: X, Y, Z Yaw, Pitch, Roll or WPR
Tool Coordinate System

- The world frame defines the coordinate system where things are located, the tool frame origin or tool center point (TCP) is the ‘thing’ or particular point on the robot being located.
- The default tool frame or tool0 is typically located at the center of the faceplate (where the end of arm tooling is mounted) with a right-hand rule orientated coordinate system.
Tool Coordinate System

• Multiple different tool frames can be defined for any particular robot, the definition is relative to the default tool frame.
• Typically the TCP is the point where work is done, but does not have to be.
Putting it all Together

- A robots’ Cartesian position represents the current position of the active TCP relative to either the world frame or the current active user frame.
A change in orientation will leave the TCP at the same position.
Robot Positions

- Depending on style of robot different joint configurations will yield the same Pose.

<table>
<thead>
<tr>
<th>World Position</th>
<th>Config: N U T, 0, 0, 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>X: 1293.805 mm</td>
<td>Y: -45.735 mm</td>
</tr>
<tr>
<td>Z: -70.000 mm</td>
<td></td>
</tr>
<tr>
<td>W: 180.000 deg</td>
<td>P: 0.000 deg</td>
</tr>
<tr>
<td></td>
<td>R: 0.000 deg</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Joint Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1: -2.025 deg</td>
</tr>
<tr>
<td>J2: -4.317 deg</td>
</tr>
<tr>
<td>J3: -45.051 deg</td>
</tr>
<tr>
<td>J4: 0.000 deg</td>
</tr>
<tr>
<td>J5: -44.949 deg</td>
</tr>
<tr>
<td>J6: 2.025 deg</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>World Position</th>
<th>Config: F U T, 0, 1, 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>X: 1293.805 mm</td>
<td>Y: -45.735 mm</td>
</tr>
<tr>
<td>Z: -70.000 mm</td>
<td></td>
</tr>
<tr>
<td>W: 160.000 deg</td>
<td>P: -15.000 deg</td>
</tr>
<tr>
<td></td>
<td>R: 0.000 deg</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Joint Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1: -2.024 deg</td>
</tr>
<tr>
<td>J2: -4.317 deg</td>
</tr>
<tr>
<td>J3: -45.051 deg</td>
</tr>
<tr>
<td>J4: 180.000 deg</td>
</tr>
<tr>
<td>J5: 44.949 deg</td>
</tr>
<tr>
<td>J6: 182.024 deg</td>
</tr>
</tbody>
</table>
Robot Position Configurations

- Different robots will have different robot configuration conventions and understanding them is important.
Frames Important to Vision

- World frame - default frame of the robot
- User frame - user defined frame relative to world frame
- Tool frame - user defined frame relative to face plate
When a point is recorded, it references both the Tool Frame and the User Frame.

The TCP is the point that the robot moves to a taught or commanded position.
The combination of all frames (User and Tool) and positions makes a full circle.

FP = Robot Face Plate
TF = Tool Frame
TO = Tool Offset
UF = User Frame
FO = Frame Offset
POS = Position Shown on TP

FP:TF:TO = UF:FO:POS
Position Transformations

\[ \text{FP:TO:TF} = \text{UF:FO:POS} \]
Position Transformations

\[ FP:TO:TF = UF:FO:POS \]
\[ FP:TF = UF:POS \]
\[ TF = FP^{-1}:UF:POS \]
Position Transformations

\[ TF = FP^{-1} : UF : POS \]

```plaintext
1:  DO[6;SONY]=ON ;
2:  UFRAME_NUM=6 ;
3:  UTOOL_NUM=1 ;
4:  L P[1] 500mm/sec FINE ;
5:  PAUSE ;
6:  ;
7:  UFRAME_NUM=0 ;
8:  UTOOL_NUM=0 ;
9:  PR[8:Face Plate]=LPOS ;
10: ;
11:  UFRAME_NUM=6 ;
12:  UTOOL_NUM=1 ;
13: ;
14:  VISION RUN_FIND 'FINDEOAT' ;
17: ;
19: ;
20:  CALL INVERSE(8,8) ;
21:  CALL MATRIX(8,9,7) ;
22:  CALL MATRIX(7,10,7) ;
```

\[ TF = PR[7] \]
Position Transformations

- Transform position of a part from one User Frame to another.
- Calculate $\text{PosUF2}$

$$\text{PosUF2} = \text{UF2}^{-1} : \text{UF1} : \text{PosUF1}$$
Camera Calibration

- In order to use Machine Vision to guide a robot the cameras field of view must be converted to mm from pixels.
- This is typically done with a grid of fiducials with known spacing between fiducials and some orientation feature built-in.
Camera Calibration

- Execute calibration routine with MV system.
- This will locate grid pattern and calculate a mathematical transformation from pixels to mm.
- Most will calibrate in a perspective mode allowing parts to be located at different distances from the camera provided this distance is known.
Camera Calibration

- One way to coordinate a calibrated MV camera and a robot is to define the calibration grid as a user frame or base frame, work object etc.
Camera Calibration

- Ensure point tool frame TCP definition is accurate before teaching or touching up the user frame definition of the calibration grid.
More and more robots are able to auto-calibrate by moving a target around in the field of the view of the camera and creating a set of calibration data.
Perspective vs. Orthogonal Calibration

- 2D Orthogonal Calibration will only yield accurate information for a part located at the same distance from the camera as the calibration grid was during calibration.
Perspective vs. Orthogonal Calibration

- Perspective calibration will calculate a complete mathematical model for the lens.
- This allows the camera to part distance to change but this distance needs to be known.
VGR Application Engineering

- Field of view should only be as large as necessary.
- How big is the feature being located?
- How much will it move?
- Add 10-20% in each direction.
- 50 pixels is typically plenty for most pattern matching algorithms.
• Camera resolution selection is driven mainly by size of feature in the field of view.
• VGA or 640 X 480 cameras often have enough resolution for VGR applications.
• 50-100 pixels is plenty for most pattern recognition algorithms.
Application Example

• Locate a 2’ diameter puck on a flat table.
• Part is expected to move +/- 10” from center of the table.
• Field of View should be 10”+20% = 12”X12”
Application Example

- ½” sensor camera with a 12mm lens at 725mm stand-off yields a FOV of 16X12”.
- Using a VGA (640X480) sensor yields’ a resolution of 0.025”/pixel
- Approximate number of pixels around edge of part
  \[2 \times \pi = 6.3”/0.025 \approx 250 \text{ pixels}\]
Application Example

- Moving to SXGA (1280X1024) sensor yields a resolution of 0.012”
- Approximate number of pixels around edge of part.

\[ 2\pi \approx 6.3”/0.012 \approx 525 \text{ pixels} \]

- VGA or 640X480 should be fine for this application.
Industrial Robot Accuracy

• Three elements to Robotic system accuracy
  – Robot Mastering
  – TCP or Tool Center Point
  – User Frame or Fixture

• Repeatability vs. Accuracy

Repeatable | Accurate
Industrial Robot Accuracy

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Articulated Type</td>
</tr>
<tr>
<td>Controlled axes</td>
<td>6 axes (J1, J2, J3, J4, J5, J6)</td>
</tr>
<tr>
<td>Reach</td>
<td>1359 mm</td>
</tr>
<tr>
<td>Installation (Note 1)</td>
<td>Floor, Upside-down, Angle mount</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Motion range (Maximum speed) (Note 2)</th>
<th>J1 axis rotation</th>
<th>J2 axis rotation</th>
<th>J3 axis rotation</th>
<th>J4 axis wrist rotation</th>
<th>J5 axis wrist swing</th>
<th>J6 axis wrist rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6.28 rad (3.05 rad/s)</td>
<td>2.95 rad (3.05 rad/s)</td>
<td>376° (176°/s)</td>
<td>12.57 rad (4.36 rad/s)</td>
<td>4.36 rad (4.36 rad/s)</td>
<td>12.57 rad (6.20 rad/s)</td>
</tr>
</tbody>
</table>

| Max. load capacity at wrist          | 50 kg             |
| Max. load capacity at wrist (Note 3) | 15 kg             |

| Allowable load moment at wrist       | J4 axis: 206 Nm² | J5 axis: 206 Nm² | J6 axis: 127 Nm |
| Allowable load inertia at wrist      | J4 axis: 28 kg·m² | J5 axis: 28 kg·m² | J6 axis: 11 kg·m² |
| Drive method                         | Electric servo drive by AC servo motor |
| Repeatability (Note 4)               | ±0.07 mm          |
| Mass                                 | 645 kg            |

| Installation environment             | Ambient temperature: 0~45°C Ambient humidity: Normally 75%RH or less (No dew nor frost allowed) Short term 95%RH or less (within one month) Vibration acceleration: 4.9 m/s² (0.5G) or less |

**Performance**

| Position repeatability (RP)          | 0.05 - 0.06 mm |
| Path repeatability (RT)              | 0.13 - 0.46 mm (measured at speed 250 mm/s) |

**KR 30-3**

The KR 30-3 is a masterful mover with a fist-shaped work envelope, and is ideal for the implementation of cost-effective, space-saving system concepts.

- **Loads**
  - Payload: 30 kg
  - Supplementary payload: 35 kg

- **Working envelope**
  - Max. reach: 2033 mm

**Other data and variants**

<table>
<thead>
<tr>
<th>Number of axes</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repeatability</td>
<td>±0.06 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>665 kg</td>
</tr>
<tr>
<td>Mounting positions</td>
<td>Floor, Ceiling</td>
</tr>
<tr>
<td>Controller</td>
<td>KR C4</td>
</tr>
</tbody>
</table>

**Controlled axes**

<table>
<thead>
<tr>
<th>Maximum payload [kg]</th>
<th>280</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repeatability [mm]</td>
<td>±0.2</td>
</tr>
<tr>
<td>Horizontal reach [mm]</td>
<td>2,446</td>
</tr>
<tr>
<td>Vertical reach [mm]</td>
<td>2,962</td>
</tr>
<tr>
<td>Temperature [°C]</td>
<td>0 to +45</td>
</tr>
<tr>
<td>Humidity [%]</td>
<td>20 - 80</td>
</tr>
<tr>
<td>Weight [kg]</td>
<td>1,120</td>
</tr>
<tr>
<td>Power supply, average [kVA]</td>
<td>5.0</td>
</tr>
<tr>
<td>Internal I/O cable [conductors w/ ground]</td>
<td>24</td>
</tr>
<tr>
<td>Internal air line [connections]</td>
<td>(2) 3/8”</td>
</tr>
</tbody>
</table>
Each robot has a unique 'signature', affecting positioning accuracy

- Joint zero positions / Mastering (M)
- Link lengths (L)
- Twist angle (T)
- Gravity Compensation (G)
Using Vision Information to Guide Robot

• Start with a well mastered robot
  – Joint angles and Kinematics create a good World Frame (Joint angles translated into Cartesian Coordinates)

• Create reference positions of the calibration grid to the robot
  – Where is the grid in robot space? The Origin, X and Y directions

• Calibrate the vision system to:
  – Tie the calibration grid position and orientation to what is seen by the camera
  – Render pixels per unit of measure
Using 2D Vision Information to Guide a Robot

- Use absolute vision information to move robot tooling to part.
- Accurate Utool definition is required for this approach.
Using Vision Information to Guide Robot

- Using a coordinate system which is the same as the calibration grid the Utool can be moved to the part position as discovered by vision.
Using Vision Information to Guide Robot

- Since Calibration Grid was defined at table surface robot tool frame is moved there.
- Need to adjust found position Z value to match part height

```plaintext
1:  UFRAME_NUM=5
2:  UTOOL_NUM=1
3:  J  P[1] 100% FINE
4:  CALL VISION('PART1')
6:  L @PR[11:Found Pos] 500mm/sec FINE
```
Using Vision Information to Guide Robot

- A reference position and offset approach can be used.
- Once camera is calibrated and part feature trained place part in an arbitrary position in field of view and record this as nominal or reference position.
Using Vision Information to Guide Robot

- Teach robot handling or processing positions to this reference part
At run time the difference between the discovered part position and reference position is calculated and applied to previously taught robot positions.

\[ \text{Offset} = \frac{\text{Fnd Pos}}{\text{Ref Pos}} \]
Using Vision Information to Guide Robot

- Accurate Utool definition is not required for this approach.
- Amount of distance relying on robot accuracy is minimized.
• Height change creates subtle apparent size change.
• Are you sure the part size is not different – creating the same affect?
Use Focal Length to Calculate Distance

Known:

- Calibrated Focal length of Lens
- Camera Array size
- If Part size is known, calculate distance of the part from the camera
Depth Using Consistent Part Size

- Find parts at two known heights and set data.
- This will define scale, layer, and height relation.
In two-dimensional applications, the XY plane of the user frame specified here should be parallel to the target work plane. How do you compensate when this is not the case?
Vision To Robot Transformations Considerations

• Camera mounting style
  – Fixed position or Robot mounted camera
    • Cycle time
    • Size of part (FOV) vs. accuracy needed
    • How big is the feature how much will it move
    • Vision accuracy can be sub-pixel

• Part Presentation issues
  – In which axis's is the part likely move?
    • X, Y, Rotation, Z, Pitch and Yaw
  – Is the part consistent and is its presentation consistent
  – Is it possible to correlate position from different perspectives?
  – Can structured light be used to help identify location?
2D Robotic Assumptions

• 2D imaging systems can be used if:
  – The part always sits flat on a surface or fixture (no pitch or yaw changes)
  – The part is consistent in its size and shape
  – The tool is designed to compensate for any variation in height (and subsequent X, Y error)

• 2D is not a good solution when:
  – Parts are stacked and may be subject to tipping
  – Parts are randomly placed in a bin for picking
  – Parts enter the robot cell on a pallet that is damaged, or on a conveyor that wobbles
  – High accuracy assembly process like hanging a door on an automobile
Lighting Impacts Part Position (Perspective)

- Perceived location of a part can shift due to lighting
- Locate the center of the top surface

- Which lighting method provides stable features for the vision system to locate?
Example 3D VGR Applications

- Racking and De-racking
- Palletizing and Depalletizing
- Welding uneven surfaces
- Grinding and flash removal
- Machine load
- High accuracy assembly
- Parts on Hangers
- Picking Stacked parts
- Picking parts randomly located in bins
Common Methods for 3D Vision Position Extraction

• Use known geometric relationships to calculate position
• Stereo Triangulation
• Structured Light
• Single Camera 3D
• Laser Triangulation
• Time of Flight Imaging
• Moiré Interferometry, Pose from shadow, depth from focus
Stereo Method

- Camera Pixels represent rays originating at the cameras lens
- Multiple rays converge to form points X,Y and Z
- Multiple Points form a plane (at least 3 points are required)
Stereo Triangulation Method
On round parts, transformations may not be applied to exactly the same point – creating the possibility of error.
Stereo Multiple View Example

Locate the 3D position of a large rigid work surface or object

Requires a minimum of 3 positional views. 4\textsuperscript{th} is used for improved fit calculations.
Planar Relationships

- Using (4) 2D camera views pointing inward toward a large rigid body the 3 dimensional (3D) position can be determined.
Applying Geometric Relationships

- Identify fixed and reliable geometric features (corners or holes)
- Apply Geometric Position Relationships between features
- Compensate for Perspective
Geometric Relationships

- Start with a known shape
- Extract feature Point Position with respect to calibrated cameras
- The part shape is assumed to be constant although position is not
- Combine camera position relationship with found feature to extract new position
Triangulation Method for 3D Rendering

- Instead of comparing image data, this method uses light projected at an angle.
- The relationship of the light to the camera is known.
- Laser light provides high contrast
- Laser line projection provides surface relationship data
Triangulation Method for 3D Rendering

Structured-light projector

2D Machine Vision Camera

![Diagram of structured-light projector and 2D machine vision camera](image)

![Image of iRVision Setup Main - VP3DL](image)
3D Point Clouds

- There are many 3D vision sensors which generate a point cloud
3D Point Clouds

• A point cloud is a grid of XYZ points which digitizes a 3D scene
Analyzing Point Cloud

- Many software packages exist for point cloud 3D part location extraction
- Some rely on 3D CAD of part, others relay on looking for basic 3D Shapes.
Single Camera 3D

• Using advanced algorithms full 3D information can be obtained from single 2D image referencing 3D CAD of a part.
• Process intensive and can have issues with occluded parts.
Guiding Robot with 3D Information

- Concept and approaches are the same for 3D vs. 2D.
- Reference/Offset mathematics is the same for 3D.

\[
\text{Offset} = \text{Fnd Pos} : \text{Ref Pos}^{-1}
\]
Bin Picking

• Vision is used to:
  – Find the Bin
  – Find the part
  – Make sure not to collide with the bin walls
  – Pick the part with the robot tool at the correct angle
Bin Picking

• Often a combination of 3D vision and 2D vision is used to fully realize a bin picking system.
Bin Picking

- Often a combination of 3D vision and 2D vision is used to fully realize a bin picking system.
Approximately 14% of MV systems sales are 3D.

2D systems traditionally “X, Y and rotation”, whereas 3D systems provide “height, pitch and yaw”, too.

3D allows robots to place vacuum cups squarely on a flat surface, or pick a part so it is square to the tool.

Why not use 3D vision on all robot systems?

- Cost.
- Processing time.
Summary

• Robotic Vision is all about determining location

• Maintain Critical Relationships through calibration
  – Robot to Frame (Grid)
  – Frame to Camera
    • Orientation, direction and distance from the camera
  – Robot to Part

• How the part presents itself to the camera determines what type of vision is needed
  – 2D
  – 2.5D
  – 3D
David Bruce
Engineering Manager

FANUC America Corporation
3900 West Hamlin Road
Rochester Hills, Michigan
USA

Phone: +1 248-377-7151
Cell: +1 248-830-8862
Email: david.bruce@fanucamerica.com

www.fanucamerica.com