RUSSIAN STATE SCIENTIFIC CENTER FOR ROBOTICS AND TECHNICAL CYBERNETICS (RTC)

3D modeling of an object located in the underwater robot's manipulator workspace using a point cloud

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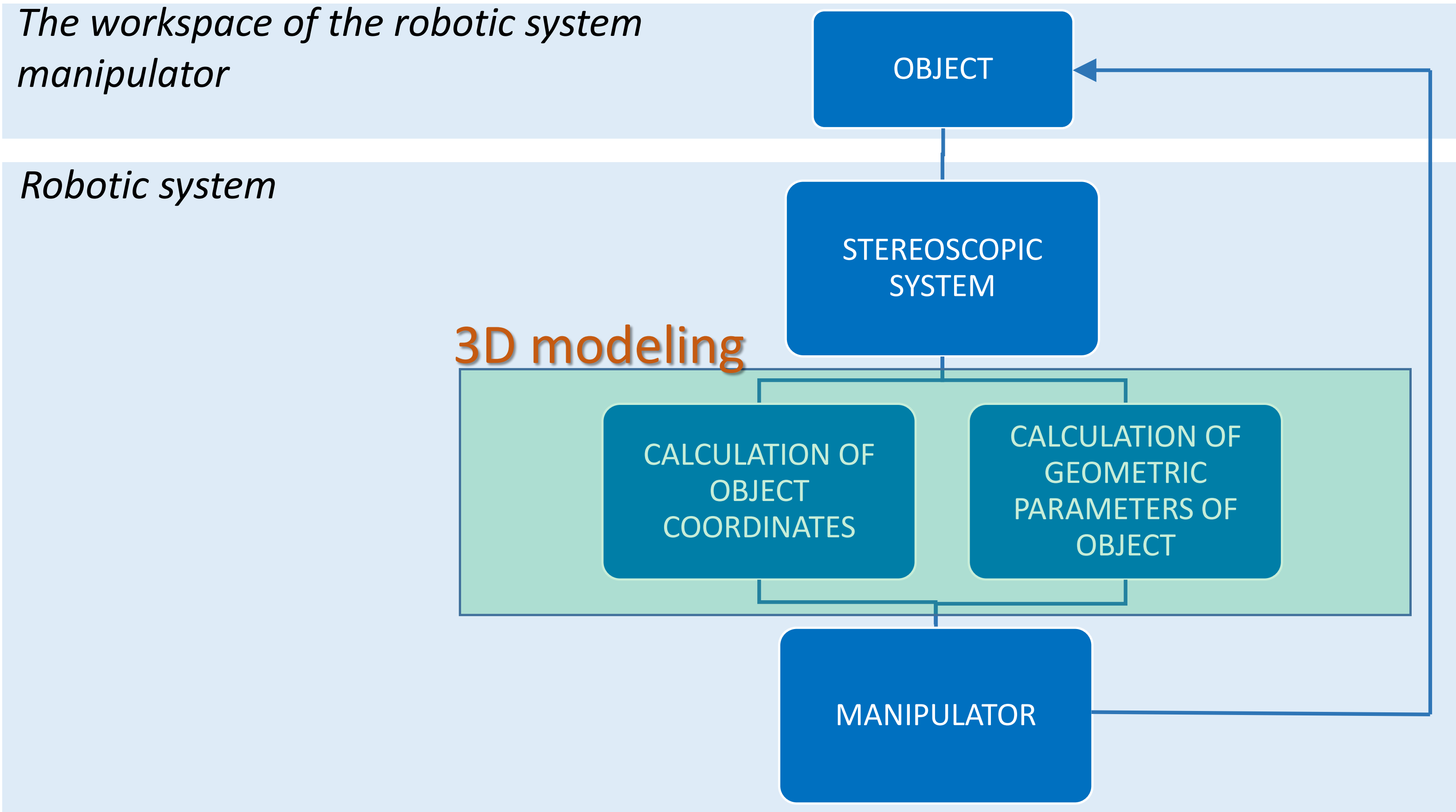
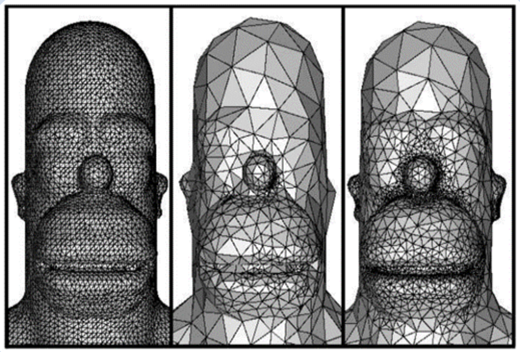
Statement of the problem

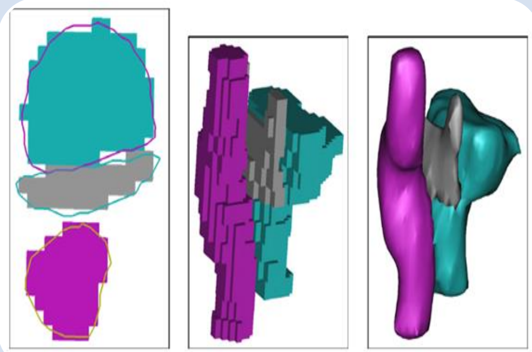


3D modeling methods

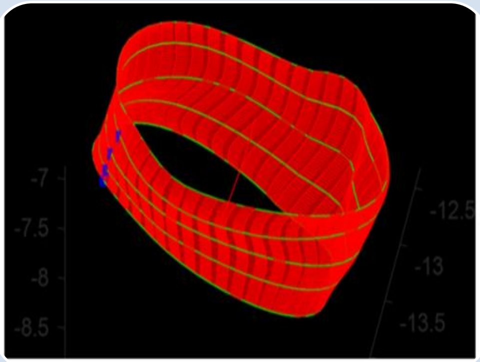
POLYGONAL MODELING



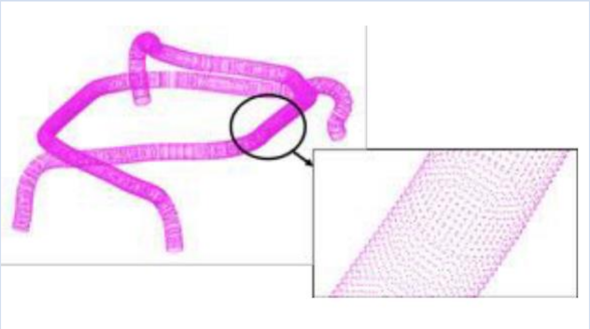
VOXELS-BASED MODELING



NURBS-BASED MODELING



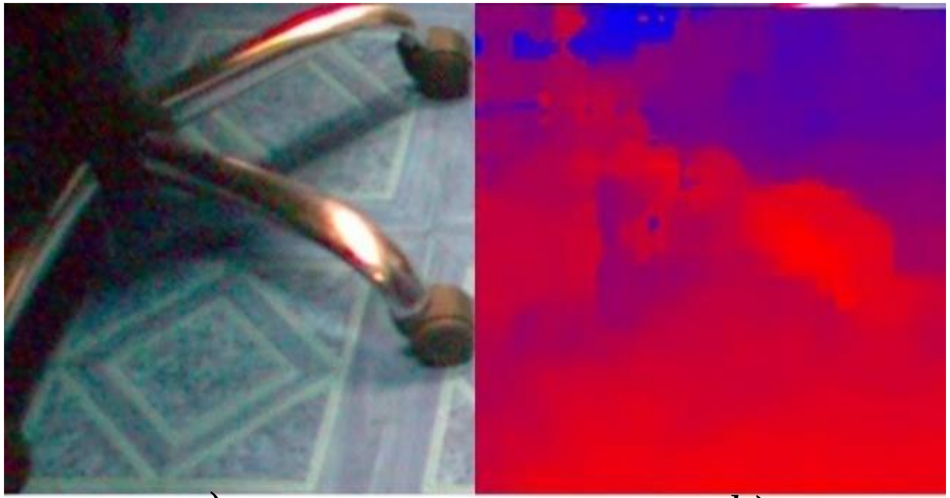
APPROXIMATE DESCRIPTION OF AN OBJECT AS A ROTATION SHAPE



- Allows us to collect information about the geometric dimensions and the shape of the object using a noisy and incomplete point cloud.
- Variability
- Does not require the construction of the surface as whole, that which allows us to reduce computational resources utilized by onboard control system of the robot.

Proposed solution - division into cross line segments. Initial data

- Point cloud obtained from the stereoscopic system.
- Each image pixel corresponds to a triple of metric coordinates (x, y, z) in the coordinate system of the manipulator.
- A pre-selection (rejection) of the points from the 3D point cloud.



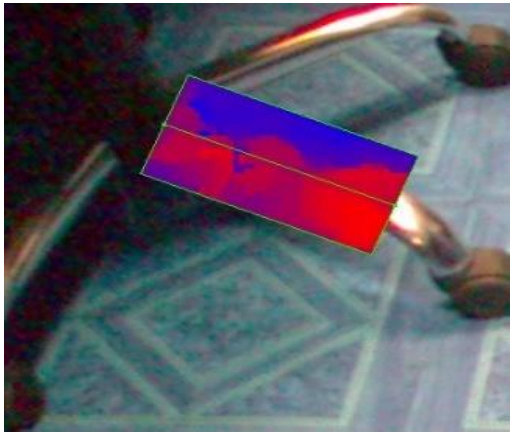
a) b)

Initial image (a) and the same image with the point cloud projected onto it - a depth map (b).

Proposed solution - division into cross line segments. Initial data

- Operator sets the area of interest (object’s axis and the width of the area in pixels) and approximate object description.

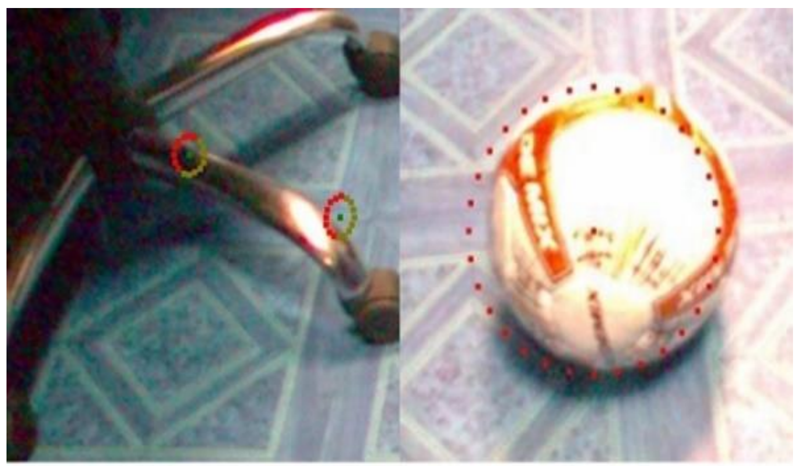
Object	Approximate object description	Processing tool
The underlying surface	Plane	GeoSampler
Pipe (extended, cylindrical)	Cylinder	Mechanical cutter
Rod (extended, thin)	Segment	Clipper
Chip, dangerous object (compact)	Sphere, cone	Grip of the manipulator



Area of interest and point cloud points belonging to it.

Proposed solution - division into cross line segments. Expected results

- A mathematical and computer model of the object.
- The information about the geometric dimensions and the shape of an object without the construction of the surface.
- Re-projection onto the initial image.



a)

Re-projection of the bases of the constructed cylinder (a) and a diametric cross section of the constructed sphere (a) onto the initial image.

Solved tasks

- Formation the cross segments of the area of interest.

For each pixel comprising object's axis, a linear equation was calculated for the lines perpendicular to the object's axis. The segment of the calculated line was formed using the width of the area in pixels.

- Object segmentation the points of the area of interest based on z-axis.
- Calculating the center and the radius of the circumcircle of the cross segments.
- Description the segmented object as a cylinder and as a sphere:

- constructing the central axis of the rotation shape;
- calculating the radius of the rotation shape.

Solved tasks. Object segmentation the points of the area of interest based on z-axis.

1. Calculating the mean *z*-coordinate for every pixel in the segment:

$$\bar{z} = \frac{1}{k+1}\sum_{i=0}^{k} P_{z,i}^{c,n} \quad , \qquad (1)$$

where *k* - number of pixels in the segment, $P_{z,i}^{c,n}$- *z*-coordinate of the point in the point cloud corresponding to pixel *i* of segment *n*.

2. If $P_z^{c,n} > \bar{z}$ is true for a pixel, it is then removed from the set $\{P^{c,n}\}$ The value was recalculated using equation (1). The result of the calculation is illustrated by figure. The "distant" pixels are shown in navy blue, while the "close" pixels were shown in light blue.

3. Calculating the standard deviation (σ) for the *z*-coordinate of the "close" pixels for the area of interest looks like:

$$\sigma = \left(\frac{\sum_{i=0}^{k}(P_{z,i}^{c,n} - \bar{z})^2}{k+1}\right)^{1/2} \qquad (2)$$

Solved tasks. Object segmentation the points of the area of interest based on z-axis.

4. Recalculation 1-3.
5. If (3) is true for a pixel, it was removed from the set {*Pc,n*}.

$$\left|P_{z,i}^{c,n} - \bar{z}\right| > 3 \cdot \sigma \qquad (3)$$

6. Pixels were added to the set $\{Pc,n\}$ based on three-sigma criteria.

Moving from left to right (4) and from right to left (5):

$$(\cdot)(i,j) \in \{P^{c,n}\} \leftarrow \left|(i,j)_z - P_{z,i-1}^{c,n}\right| \leq 3 \cdot \sigma. \qquad (4)$$

$$(\cdot)(i,j) \in \{P^{c,n}\} \leftarrow \left|P_{z,i+1}^{c,n} - (i,j)_z\right| \leq 3 \cdot \sigma. \qquad (5)$$

The result of the calculations according to 3-6 is illustrated in Figure. "Distant" pixels were shown in navy blue; pixels forming the set $\{P^{c,n}\}$ (from the calculations according to 5-6) were shown in yellow.

Solved tasks. Object segmentation the points of the area of interest based on z-axis.

The resulted set $\{P^{c,n}\}$ was filtered using two thresholds:

- the required density (T_d) of the pixels that passed the filtration procedure according to 1-6 was compared to all the points in the point cloud belonging to the longitudinal segment *n* of the object.$P_{cl}^{L,n}$;
- the required density (T_{de}) of the points in the point cloud belonging to the longitudinal segment *n* of the object $P_{sg}^{L,n}$compared to the length of the longitudinal segment as whole.

$$\{P^{L,n}\} \neg\in \{P\} \leftarrow \left(\frac{\sum_i P_i^{L,n}}{P_{cl}^{L,n}} < T_d \cap \frac{P_{cl}^{L,n}}{P_{sg}^{L,n}} < T_{de} \right) \quad (6)$$

The result of the filtration is illustrated in Figure. "Distant" pixels were shown in navy blue, and the segmented object was shown in red.

Solved tasks. Calculating the center and the radius of the circumcircle of the cross segments.

Each cross-segment *n* of the object on the screen ($P^{c,n}$) corresponds to a plane in the space.

For each cross-segment $P^{c,n}$ ($n = 0..P_{sg}^{c,n}$) the following list of actions was performed:

1. Detecting the base points for the circle construction:

- detecting the first segmented point inof the segment $\boldsymbol{S}(S_x, S_y, S_z) = P_0^{c,n}$;
- detecting the last point in of the segment $\boldsymbol{F}(F_x, F_y, F_z) = P_k^{c,n}$, where *k* - number of segmented pixels in the segment $P^{c,n}$;
- detecting the middle point in of the segment $\boldsymbol{C}(C_x, C_y, C_z) = P_{k/2}^{c,n}$.

2. Calculating the directional vectors of lines ***SC*** and ***CF***.
3. Calculating the coefficients for the equation of plain *SCF*:

$$A_{SCF} \cdot x + B_{SCF} \cdot y + C_{SCF} \cdot z + D_{SCF} = 0 \ , \qquad (7)$$

Solved tasks. Calculating the center and the radius of the circumcircle of the cross segments.

4. Calculating the coefficients for the equations of the plains α and β, which are perpendicular to segments ***SC*** and ***CF*** and intersect them in their middle.

5. Calculating the coordinates of the intersection point (*O*) of the plains *SCF*, α, and β. The point *O* is the sought-out center of the circle and was found by solving the following system of linear equations:

$$\begin{cases} A_{SCF} \cdot x + B_{SCF} \cdot y + C_{SCF} \cdot z + D_{SCF} = 0 \\ A_{\alpha} \cdot x + B_{\alpha} \cdot y + C_{\alpha} \cdot z + D_{\alpha} = 0 \\ A_{\beta} \cdot x + B_{\beta} \cdot y + C_{\beta} \cdot z + D_{\beta} = 0 \end{cases}, \tag{8}$$

The radius of the circle corresponding to the cross segment *n* in the object was calculated using the following equation:

$$R^n = \left((O_x - S_x)^2 + (O_y - S_y)^2 + (O_z - S_z)^2\right)^{1/2} \tag{9}$$

Solved tasks. Description the segmented object as a cylinder

Let $\{O\}$ be the set of points corresponding to the centers of the circles built from the set of points $\{P^c\}$.

To get straight-line equations $y = ax + b$ for all the points from the set $\{O\}$, the method of least squares was used. The coefficients a and b of the equation can be found from the following equations:

$$\begin{cases} a = \left(\frac{\sum_{i=0}^{N-1} O_{x,i} \cdot O_{y,i}}{N} - \frac{\sum_{i=0}^{N-1} O_{x,i}}{N} \cdot \frac{\sum_{i=0}^{N-1} O_{y,i}}{N}\right) \cdot \left(\frac{\sum_{i=0}^{N-1} (O_{x,i})^2}{N} - \left(\frac{\sum_{i=0}^{N-1} O_{x,i}}{N}\right)^2\right)^{1/2} \\ b = \frac{\sum_{i=0}^{N-1} O_{y,i}}{N} - a \cdot \frac{\sum_{i=0}^{N-1} O_{x,i}}{N} \end{cases} \quad (10)$$

where $(O_{x,i}, O_{y,i})$ - the coordinate of the point i from the set $\{O\}$, N - number of points in the set $\{O\}$.

Calculating the distance $O_{d,n}$ from each point O_n belonging to from the set $\{O\}$ to the line:

$$O_{d,n} = \frac{\left|a \cdot O_{x,n} - O_{y,n} + b\right|}{(a^2 + 1)^{1/2}} \quad . \quad (11)$$

Solved tasks. Description the segmented object as a cylinder

The mean distance (O_d) from each point {O} to the line is calculated as follows:

$$O_d = \frac{1}{N} \cdot \sum_{i=0}^{N-1} O_{d,i} \quad . \qquad (12)$$

- In the case $O_{d,n} \geq O_d$ were true for this concrete a point, it was then removed from the set {O}. The same operations are then repeated for the projections of the points onto the plane *Oxz*.
- Calculating the radius of the cylinder *R* was performed according to the following list of actions:

1. Calculating the mean radius of the circles constructed from {P}*:*

$$\bar{R} = \frac{1}{N} \cdot \sum_{i=0}^{N-1} R_i \ , \qquad (13)$$

where *N* - size of the set of all R^n ({R}) (9)

Solved tasks. Description the segmented object as a cylinder

2. Calculating the mean linear deviation for each R_n:

$$\rho = \frac{1}{N}\sum_{i=0}^{N-1}|\bar{R} - R_i| \ . \tag{14}$$

3. If $R_n > \rho$ is true for a point, it is removed from the set $\{R\}$.
4. Repeating 1-3 M times.
5. Calculating the cylinder radius:

$$R = \frac{1}{\mathrm{N}}\sum_{i=0}^{N-1} R_i \ . \tag{15}$$

Solved tasks. Description the segmented object as a sphere

There are two approaches to description an arbitrary object as a sphere:

1. Constructing the central axis (for a sphere that would be that one corresponding to the diameter of the cylinder) and calculating the radiuses R_n for each resulting cross section of the object, that has been illustrated in the previous sections. The resulting radius values of radiuses are then circumscribed into the circle using the method of least squares.

2. It is, in essence, an addition to the calculations from the previous sections. In place of the equation (15) the sought-out sphere radius is calculated as half of its axis' length:

$$R = \frac{1}{2}\left((O_{x,0} - O_{x,N-1})^2 + (O_{y,0} - O_{y,N-1})^2 + (O_{z,0} - O_{z,N-1})^2\right)^{1/2}, \quad (16)$$

where N - size of $\{O\}$.

Experimental results

- The initial data consists of an image from the stereoscopic system and a previously filtered point cloud.
- A mathematical model described in section 3 was realized using the *C++* programing language.
- To visualize the resulting mathematical model, a re-projection of a spatial shape onto the initial image was performed.

a)

Re-projection of the bases of the constructed cylinder (a) and a diametric cross section of the constructed sphere (a) onto the initial image.

Experimental results

a) *b)* *c)*

Figure 5. Initial image of the wires (a), the initial image with a point cloud projection (b), with a re-projection (c).

Experimental results

Object in question	Actual diameter, mm	Diameter obtained experimentally, mm	Error, %
Cylindrical chair leg	36	32	**11**
Soccer ball	21,6	19,2	**11**
Street wire	25	22	**12**

The comparison of real and calculated dimensions provided only moderate coincidence of 11-12%, that could be explained by *inaccuracy of the stereoscopic system* calibration and in *algorithm used for calculation of the center and the radius of the circle*.

Presumably **the error could be reduced** if the calculations were performed using methods of estimating the parameters of the model using a sample (*least-squares method, RANSAC method*).

Conclusion

The task	• 3D modeling of an object located in the underwater robot's manipulator workspace using a point cloud • information on the geometric dimensions and the shape of an object
Initial data	• Point cloud obtained from the stereoscopic system. • Operator sets the area of interest and approximate object description.
Proposed solution	• An algorithm for an approximate description of a point cloud using the method of dividing into cross segments
Advantages of the proposed method	• allows to provide information with a noisy and incomplete point cloud • doesn't require the construction of the surface. That requires less computational power needed for the robotic onboard control system. • Variability
Experiment	A mathematical description for the method was provided and tested with use of digital model. The dimensions of some objects: cylindrical chair leg, soccer ball, street wire.
Experimental results	The comparison of real and calculated dimensions provided only moderate coincidence of 11-12%. The error could be reduced using a sample (*least-squares method, RANSAC method*).

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Thank you for your attention!

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