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Digital twin-assisted automatic ship size measurement for ship–bridge collision early warning systems

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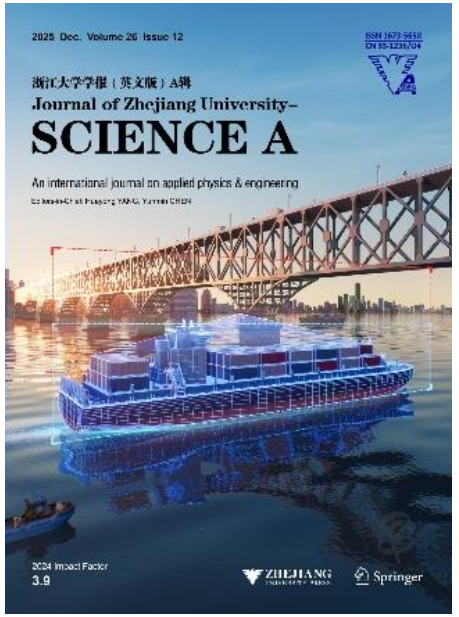
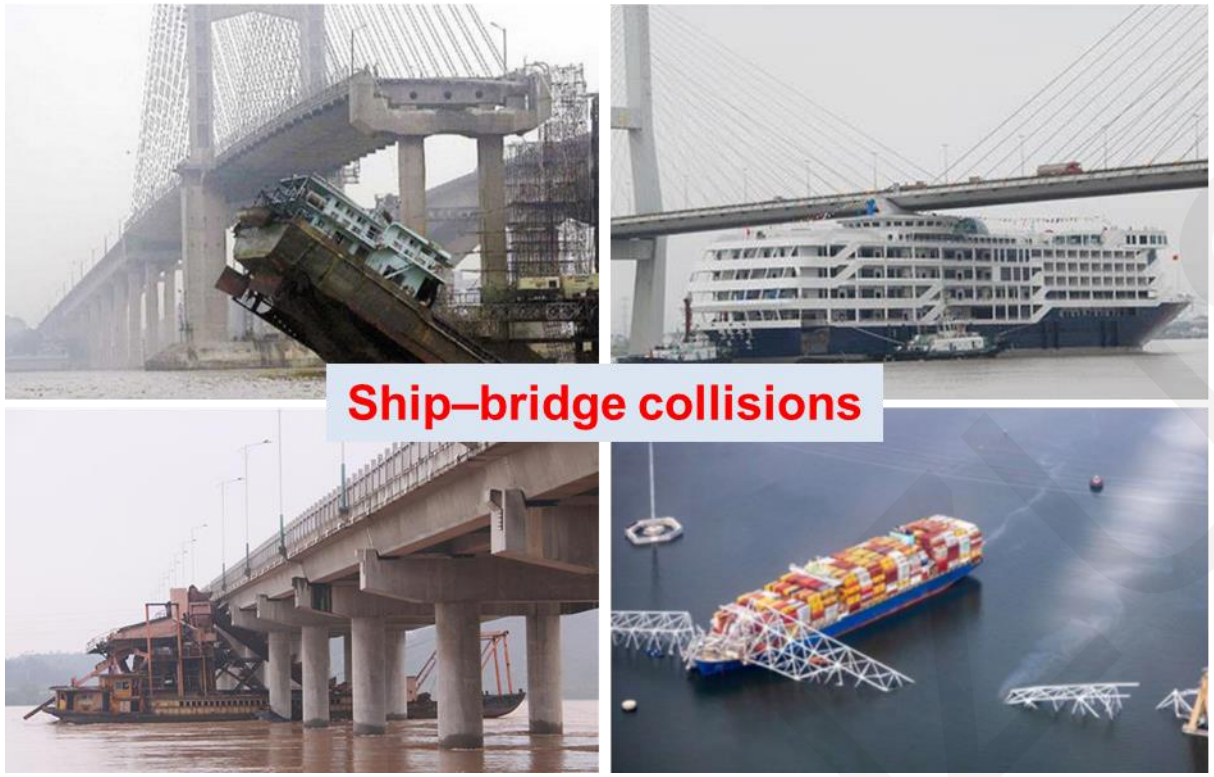


Background

Research motivation

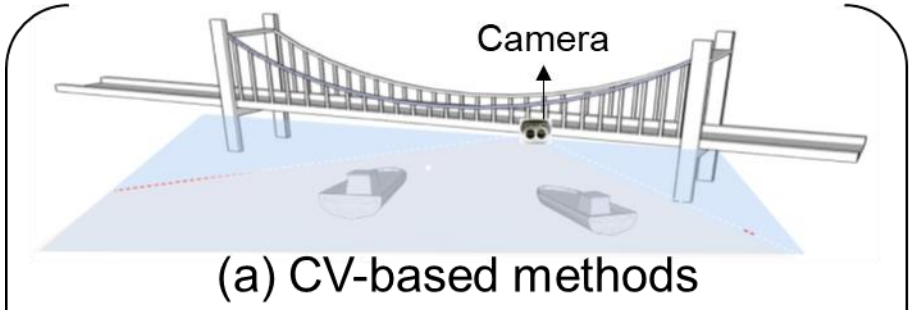




Passive anti-collision measures cannot reduce the likelihood of ship–bridge collisions, highlighting the importance of active anti-collision technologies.

Background

Research motivation



(a) CV-based methods



(b) LIDAR-based methods

Distant measurement of ship dimensions can effectively identifies oversized vessels, reducing collision risk.

Limitations

- LIDAR is costly and the detection range is limited
- CV-based methods is highly susceptible to variations in camera-to-object distances

Solutions

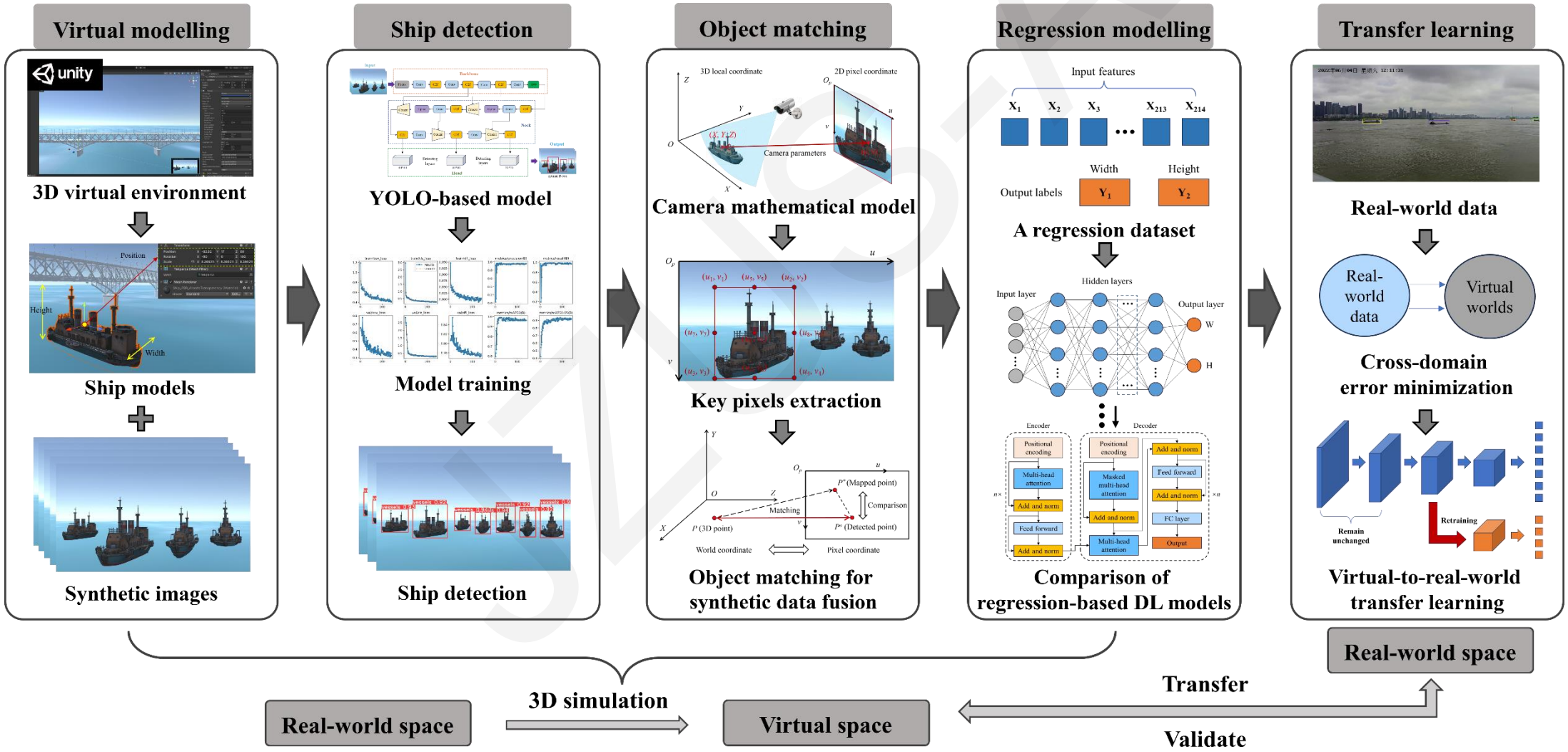
- ✓ Regression modelling
- ✓ Digital Twin (DT)
- ✓ Transfer learning



Based on these virtual data, pre-trained models can be developed and applied to various real-world cases through virtual-to-real-world transfer learning.

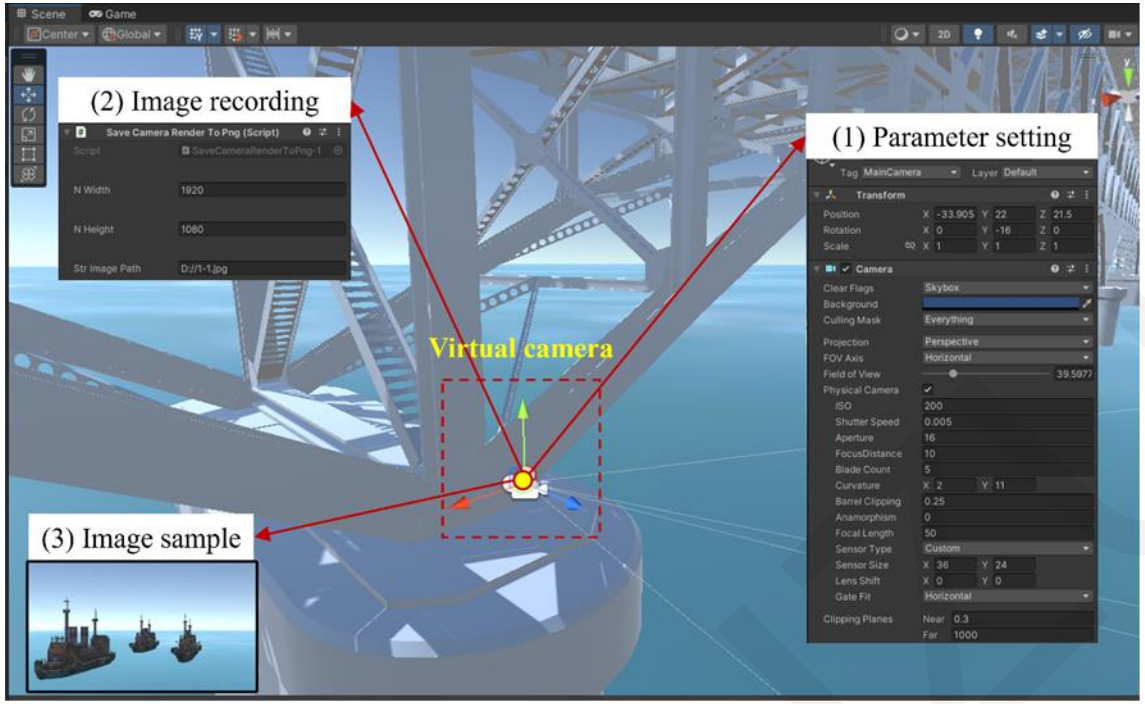
Methodologys

Framework overview

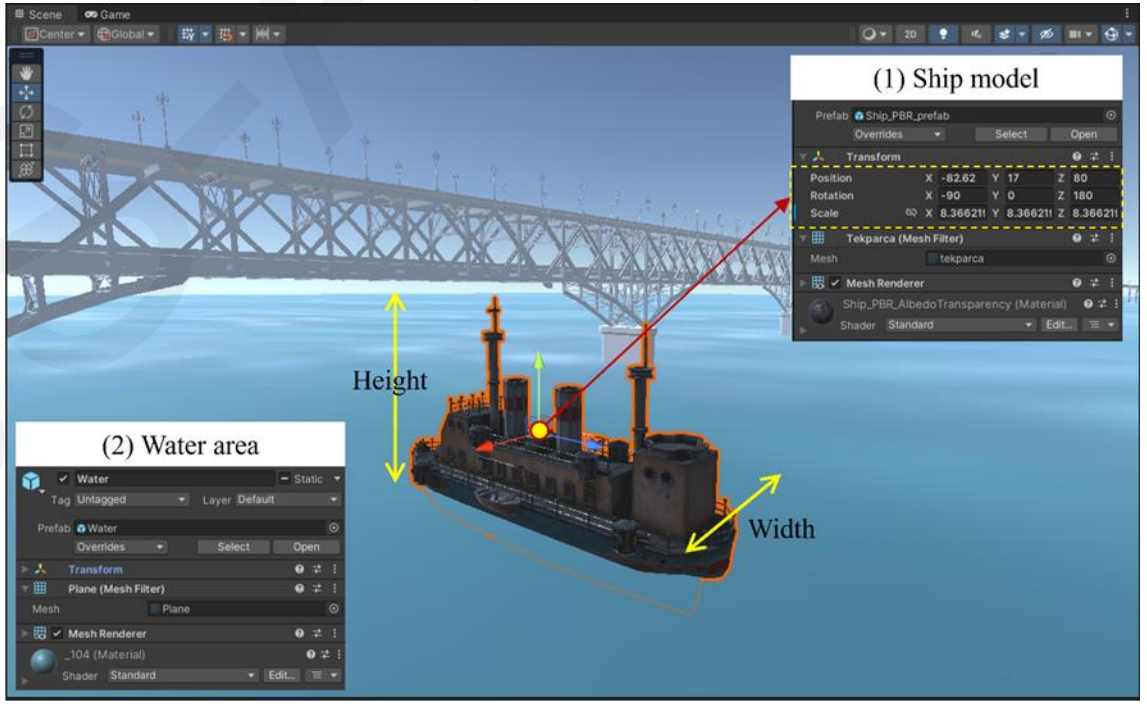


Methodologys

☐ Virtual environment establishment



(a) Virtual camera modelling

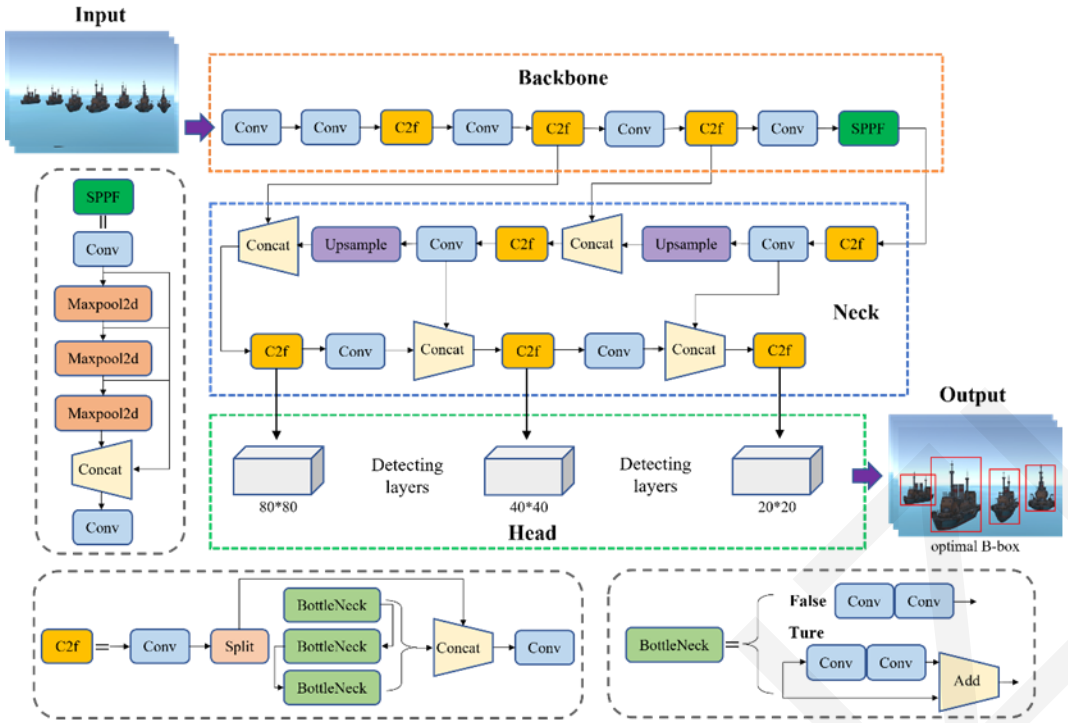


(b) Ship navigation modelling

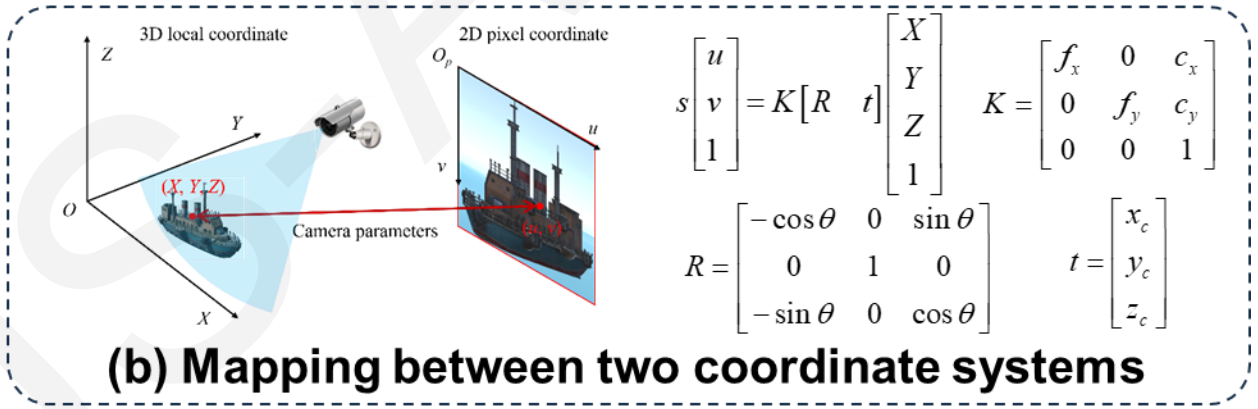
A 3D digital scene depicting the bridge navigational environment is established based on a Building Information Modelling (BIM) model and Unity3D simulation.

Methodologys

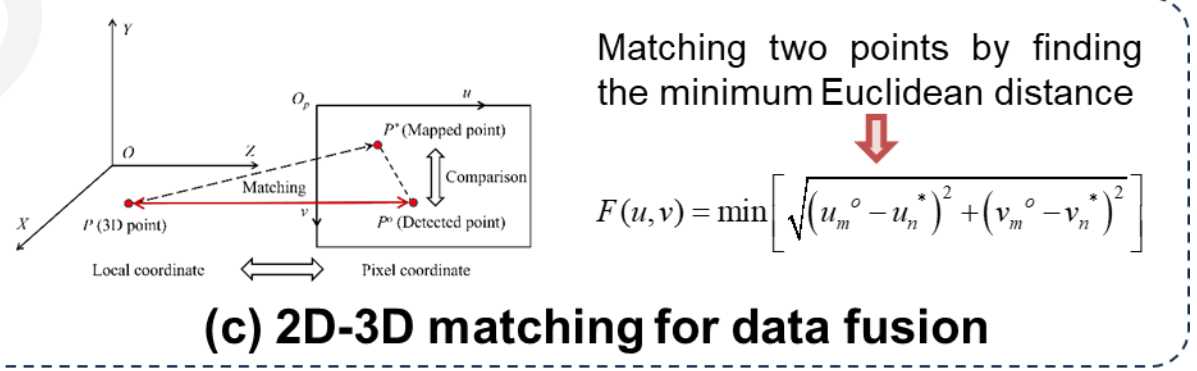
☐ Fusion of synthetic data via ship detection and object matching



(a) Ship detection model



(b) Mapping between two coordinate systems

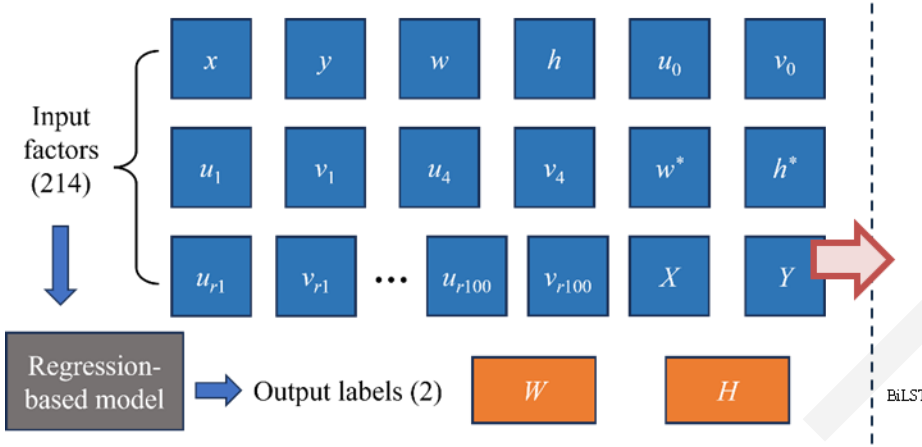


(c) 2D-3D matching for data fusion

YOLOv8 is used to extract 2D pixel information of ships from images, which is then matched with their 3D spatial coordinates.

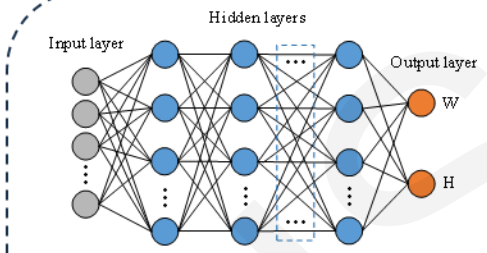
Methodologys

Regression modelling for ship sizes

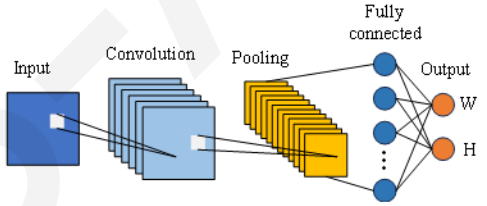


Established regression dataset

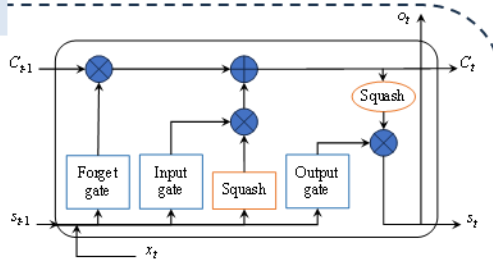
Benchmark DL models



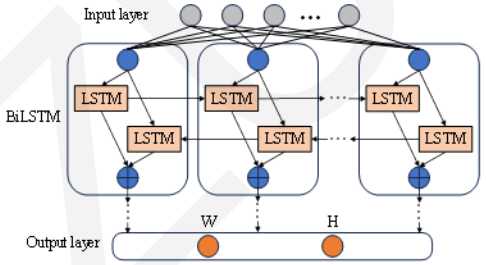
(a) MLP



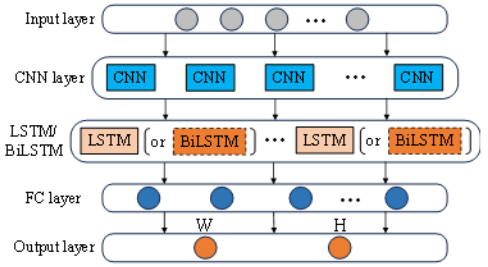
(b) CNN



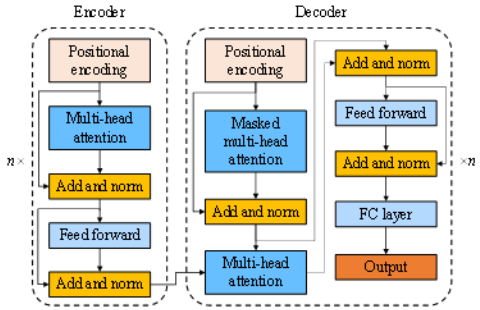
(c) LSTM



(d) BiLSTM



(e) CNN-LSTM/CNN-BiLSTM



(f) Transformer

These deep learning models will be pre-trained on the generated synthetic dataset, and the model achieving the best performance will be selected to predict ship dimensions.

Methodologys

☐ Ship size measurement by transfer learning

Cross-domain discrepancy minimization

$$\begin{bmatrix} u_{a\to s} \\ v_{a\to s} \\ 1 \end{bmatrix} = Z_s^{-1} K_s \begin{bmatrix} R_s & t_s \\ 0 & 1 \end{bmatrix}^{-1} \begin{bmatrix} R_a & t_a \\ 0 & 1 \end{bmatrix} \left(Z_a K_a^{-1} \begin{bmatrix} u_a \\ v_a \\ 1 \end{bmatrix} \right)$$

Cross-camera coordinate transformation

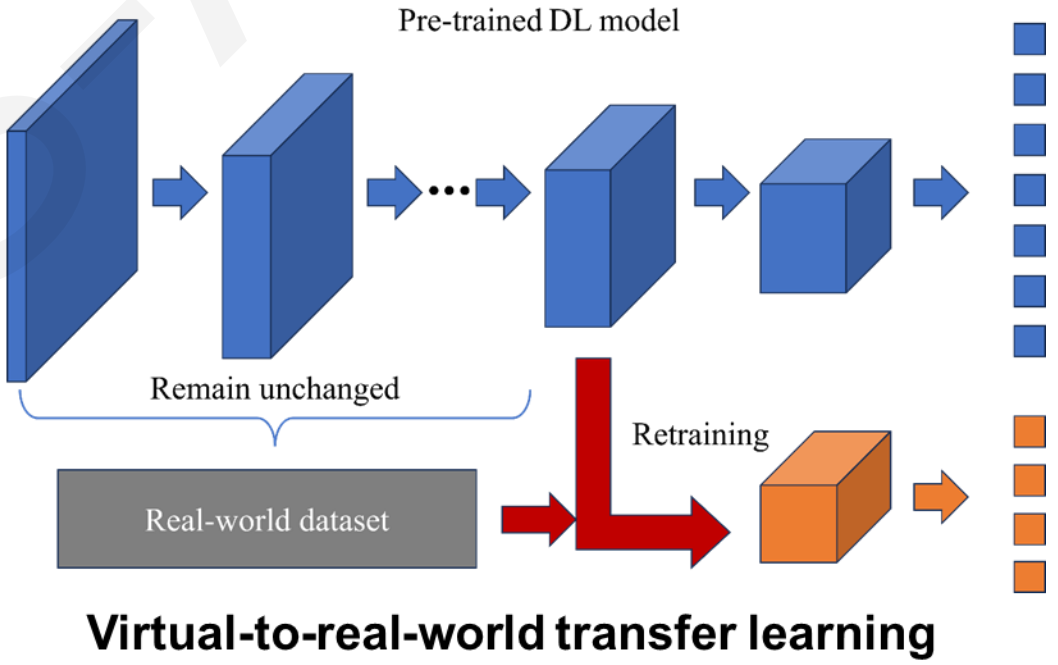
$$\begin{cases} X_e = (N_0 + h)\cos\left(\frac{lat \times \pi}{180}\right)\cos\left(\frac{lon \times \pi}{180}\right) \\ Y_e = (N_0 + h)\cos\left(\frac{lat \times \pi}{180}\right)\sin\left(\frac{lon \times \pi}{180}\right) \\ Z_e = [N_0(1-e^2) + h]\sin\left(\frac{lon \times \pi}{180}\right) \end{cases}$$

Latitude-longitude coordinates

$$\begin{cases} t_x = x_c - x_r \\ t_y = y_c - y_r \\ t_z = z_c - z_r \end{cases} \qquad \begin{cases} X_s = X_e + t_x \\ Y_s = Y_e + t_y \\ Z_s = Z_e + t_z \end{cases}$$

Virtual local coordinates

Real-world data

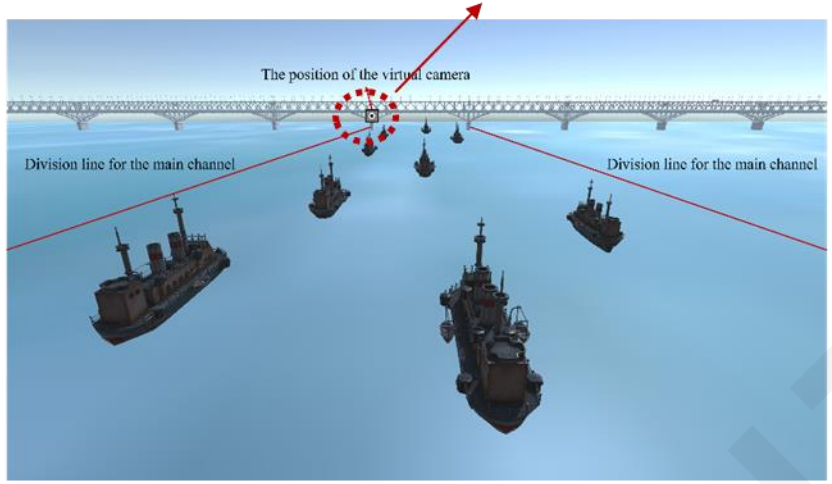


A portion of the real-world data is used to further fine-tune the pre-trained model, while the rest serves as a test set to validate virtual-to-real transfer learning.

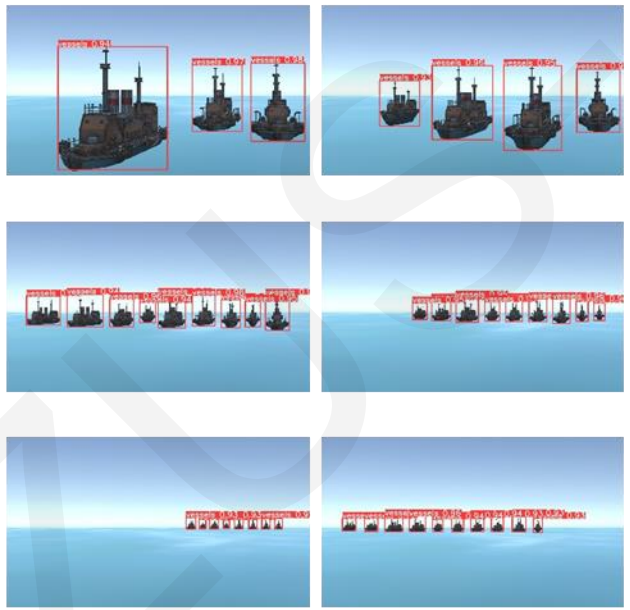
Case study

☐ Synthetic data generation and integration

FOV-H (°)	FOV-V (°)	f_x (pixels)	f_y (pixels)	c_x (pixels)	c_y (pixels)
40.598	30.372	2482	-7784	960	540



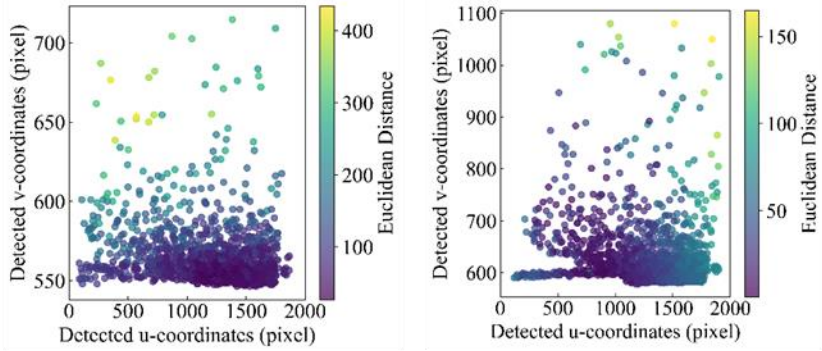
(a) 3D virtual environment



(b) Ship detection

$$s\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} 2482 & 0 & 960 \\ 0 & -7784 & 540 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} -0.961 & 0 & 0.276 & 33.9054 \\ 0 & 1 & 0 & -22 \\ -0.276 & 0 & 0.961 & -21.5 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}$$

Transformation equation



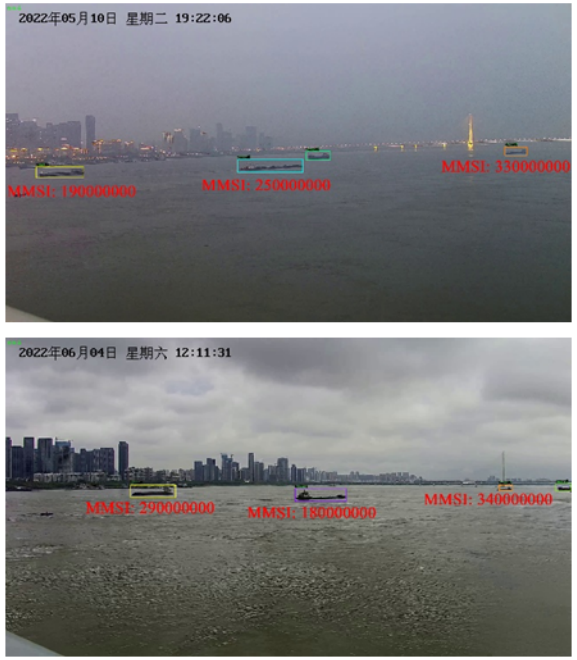
(c) Object matching

Each ship is associated with its spatial positioning, 2D-pixel information, and sizes, which collectively establish a regression dataset.

Case study

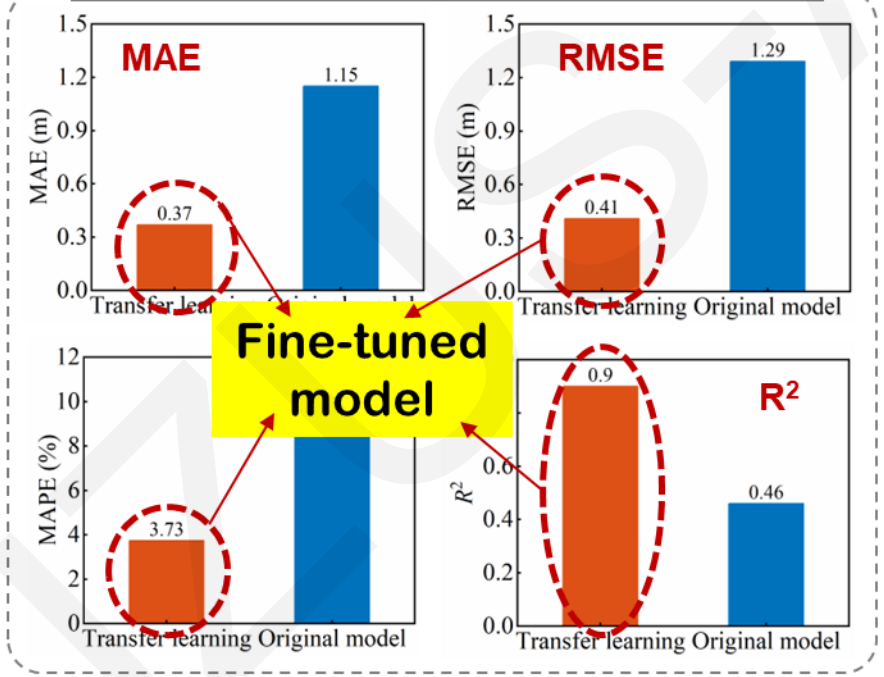
☐ Real-world ship size measurement

Data samples



https://github.com/gy65896/FVessel

Results on real-world data



Sample no.	W*(m)	W(m)	Error(m)	Relative error (%)
1	11.18	11	0.18	1.65
2	8.24	8	0.24	2.94
3	9.48	10	-0.52	-5.2
4	13.50	13	0.50	3.91
5	9.60	10	-0.60	-4.02
6	13.43	13	0.43	3.28
7	10.52	10	0.52	5.82
8	11.36	11	0.36	3.27
9	11.50	11	0.50	4.55
10	8.66	9	-0.34	-3.75
11	8.39	9	-0.61	-6.82
12	8.49	8	0.49	6.09
13	12.81	13	-0.19	-3.48
14	11.46	11	0.46	4.17
15	9.71	10	-0.29	-2.89
16	7.82	8	-0.18	-2.21
17	9.54	10	-0.46	-4.57
18	8.89	9	-0.11	-1.26

The absolute error between the actual and predicted ship sizes is mostly within 0.60 meters, which demonstrates the credibility of the measurement results.