XXVII FIG CONGRESS
11–15 SEPTEMBER 2022
Warsaw, Poland

Volunteering for the future – Geospatial excellence for a better living

Presented at the FIG Congress 2022, Warsaw, Poland 11-15 September 2022 in Warsaw

Dynamic and Precise Surveying for Water Resource Engineering —dams, bridges and pipelines

Qingquan Li[1,2,3,4], Jiasong Zhu[1,2], Dejin Zhang[1,3], Wei Tu[1,3], Chisheng Wang[1,3], Zhipeng Chen[1,3],

Siting Xiong[*,4]

1. Ministry of Natural Resources (MNR) Key Laboratory for Geo-Environmental Monitoring of Great Bay Area & Guangdong Key Laboratory of Urban Informatics & Shenzhen Key Laboratory of Spatial Smart Sensing and Services, Shenzhen University, P.R. China
2. College of Civil and Transportation Engineering, Shenzhen University, P.R. China
3. School of Architecture and Urban Planning, Shenzhen University, P.R. China
4. Guangdong Laboratory of Artificial Intelligence and Digital Economy, Kerun B, Yutang Road, Guangming District, Shenzhen, P.R. China

ORGANISED BY FIG SGP

SHENZHEN UNIVERSITY 深圳大学

GUANGMING LABORATORY 光明实验室

PLATINUM SPONSORS esri Trimble.

CONTENTS

1 **Background**
- Challenges & Opportunities in Modern Engineering Surveying
- Dynamic and Precise Surveying
- Early Research & Work

2 **Methods**
- Continuous and robust positioning and navigation in mobile and constrained scene
- Rapid sensing of multi-scale and multi-mode spatial information
- Multi-scale modelling and multi-index intepretation of surveyed object

3 **Dams** — Inertial Surveying of Internal Dam Deformation

4 **Bridges** — Vision and IMU Surveying of Long-Span Bridges

5 **Pipelines** — Multi-sensor Robot for Pipeline Surveying

CONTENTS

1 **Background**
- Challenges & Opportunities in Modern Engineering Surveying
- Dynamic and Precise Surveying
- Early Research & Work

2 **Methods**
- Continuous and robust positioning and navigation in mobile and constrained scene
- Rapid sensing of multi-scale and multi-mode spatial information
- Multi-scale modelling and multi-index intepretation of surveyed object

3 **Dams** — Inertial Surveying of Internal Dam Deformation

4 **Bridges** — Vision and IMU Surveying of Long-Span Bridges

5 **Pipelines** — Multi-sensor Robot for Pipeline Surveying

Background——Challenges & Opportunities

Infrastructure is the essential support to social and economic activities.

2010.05.23

Railway derailed
Shanghai-to-Yunnan, China
19 people died

2021.06.24

Building collapse
Miami, USA
98 people died

2011.07.14

Bridge collapse
Wuyi Mountain in
Fujian, China
1 people died

Safety Control & Health Monitoring

2020.05.19

Dam burst
Michigan, USA

2011.08.22

Subway tunnel damage
Nanjing, China

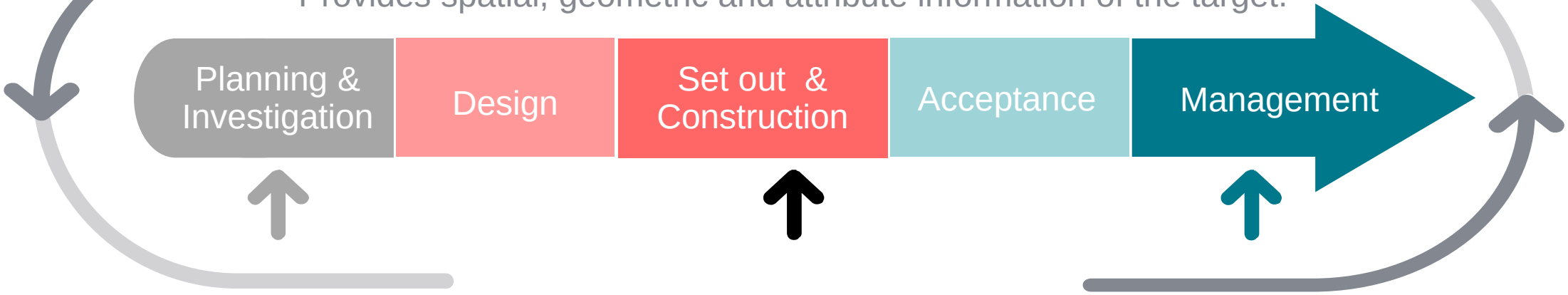
2020.01.13

Road surface collapse
Xining, Qinghai, China
4 people died

Background——Challenges & Opportunities

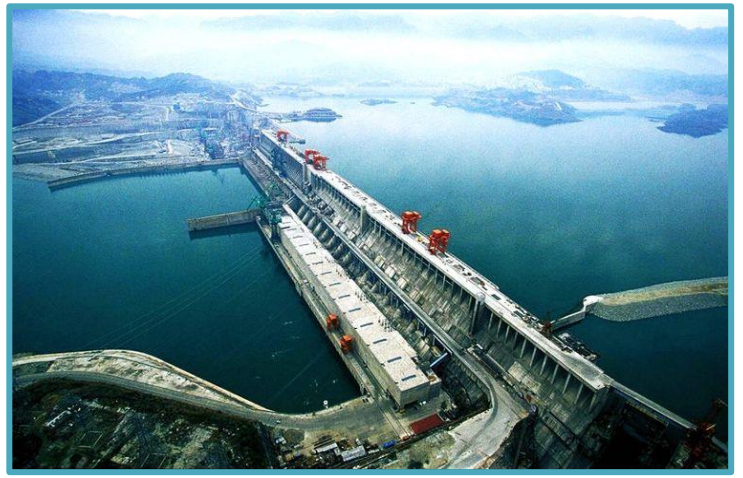
Whole lifetime of infrasctructure

Provides spatial, geometric and attribute information of the target.



exploration survey

setting out

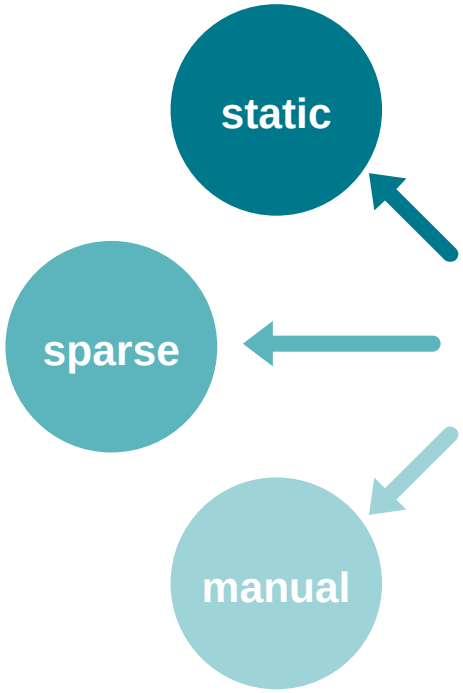


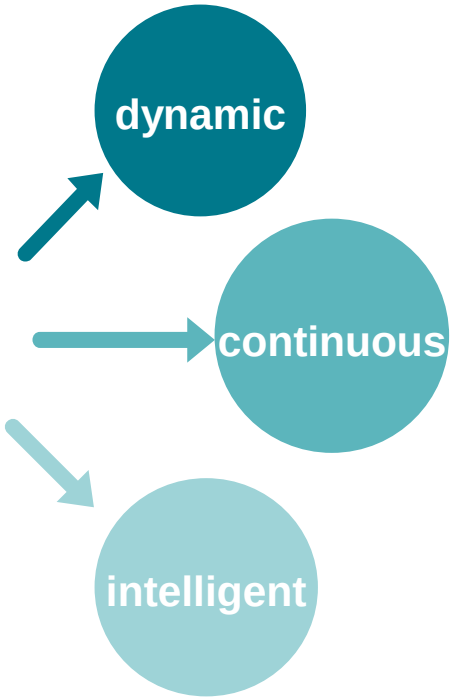
monitoring

Dynamic and Precise Surveying

Typical interdisciplinary

Multi-sensors set up on **mobile platform** to acquire various surveying data, and to extract **multi-dimension, multi-type and multi-scale features/indexes** of the object by using **intelligent data analysis.**





Dynamic and Precise Surveying

fundemental methods

1. Continuous and reliable positioning and navigation in mobile and constrained scene
2. Rapid sensing of multi-scale and multi-mode spatial information
3. Multi-scale modelling and multi-index intepretation of the surveyed object

novel techniques

rapid deflection surveying

comprehensive appearance surveying

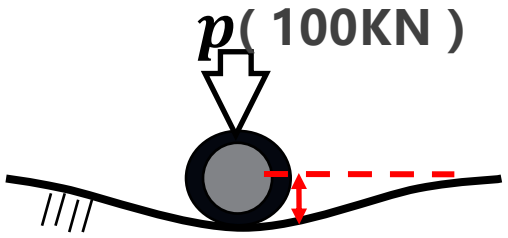
precise lining surveying

industrial applications

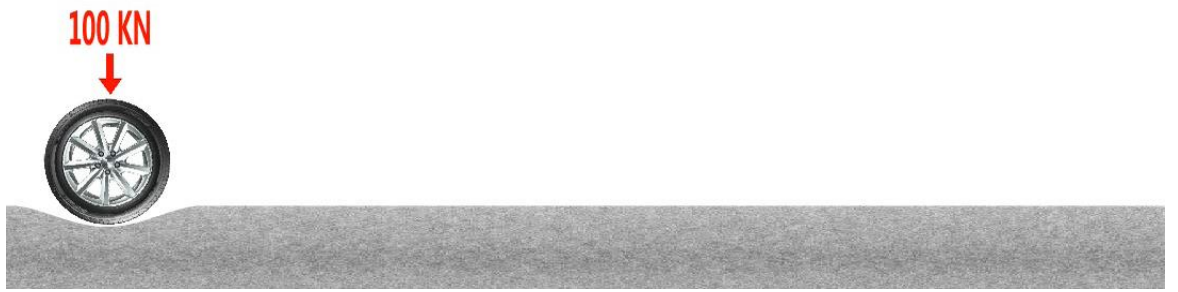
road, railway, bridge, tunnel, pipeline, dam, etc.

Early Research & Work——road surface deflection

road surface



deformation ->deflection



road deflection :
Deformation after full deformation of standard load or rebound after removal of load (unit : **0.01mm**)

Benkelman Beam

Falling Weight Deflectometer (FWD)

- efficiency: 1-3 km/h
- sampling rate: 10-50 m
- safety: high risk, traffic disturbance
- limitation: no dynamic state of the platform

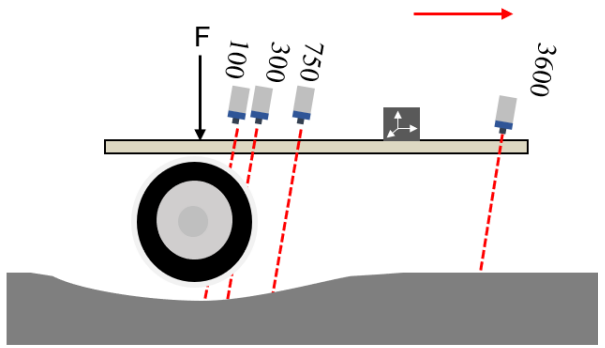
challenges

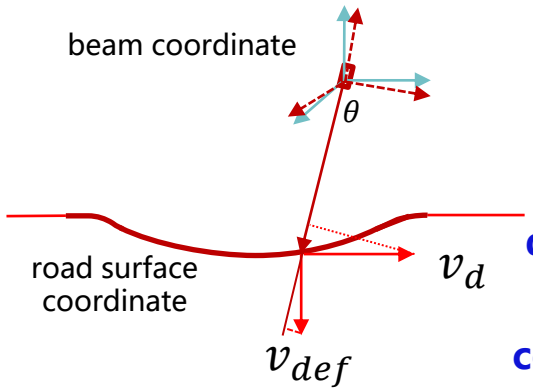
- **Full deformation** is hard to complete in **moving status.**
- Sensors and the target are both moving, leading to **large noises** which **hinders high-precision measurements.**
- Noises caused by **environmental factors, such as temperature and material variations** need to be rectified.

Early Research & Work——road surface deflection

- Inverse **road surface deflection** from **deformation velocity** measured at **multiple points around the deflection basin**.
- Measuring equipment is multiple Doppler velocimetry sensors installed on a rigid beam.

surveying mode





speed model

$$\theta = \arcsin\left(\frac{V_{dr} - V_v - V_{wr}}{V_h}\right) - \alpha_r$$

$$V_{ri} = V_{di} - V_{dr}\cos(a_i - a_r) - \frac{G_x \pi}{180}(l_i - l_r) - V_h \sin(a_i - a_r) + \varepsilon_2$$

$$\varepsilon_2 = V_{wr}(\cos(a_i - a_r) - 1) + V_h \sin(a_i - a_r)[1 - \cos(\arcsin\frac{V_{dr} - V_{wr}}{V_h})]$$

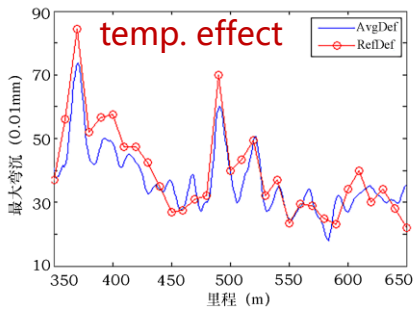
deform model

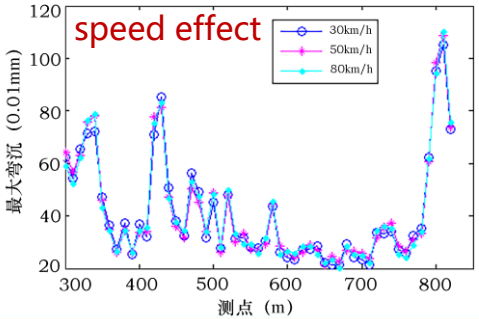
$$A'\sin(B'x_i)e^{-B'x_i} - \frac{V_{ri}}{V_h} + \Delta A\sin(B'x_i)e^{-B'x_i} + \Delta BA'x_i e^{-B'x_i}[\cos(B'x_i) - \sin(B'x_i)] = 0$$

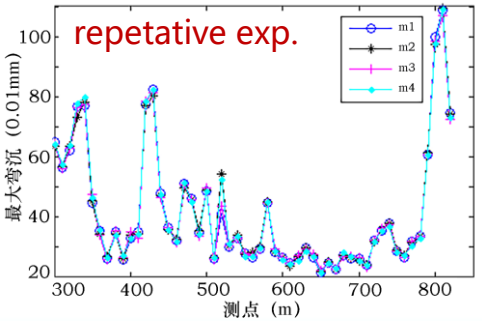
$$A'\sin(B'x_j)e^{-B'x_j} - \frac{V_{rj}}{V_h} + \Delta A\sin(B'x_j)e^{-B'x_j} + \Delta BA'x_j e^{-B'x_j}[\cos(B'x_j) - \sin(B'x_j)] = 0$$

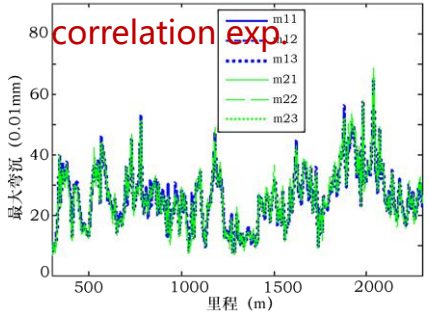
corrected model

$$F = b_0 + \sum_{k=1}^{3} b_k X_k + \sum_{k=1}^{3}\sum_{p=k}^{3} b_{kp} X_k X_p + \varepsilon$$









Early Research & Work——road surface deflection

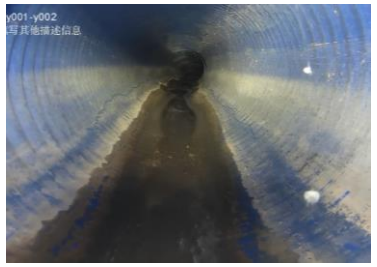
- **The first dynamic deflection measuring equipment in P.R. China,** surveying speed improved from **1-3 km/h to 90 km/h**.
- **Achieved rapid and high-precision deflection measurement** of the road network.

	achievement	TSD （Denmark）
speed	15-90km/h	20-80km/h
resolution	0.01mm	0.01mm
adaptability	rigid/semi rigid/flexible	flexible subgrade
price	2.37 million dollars	3.55 million dollars

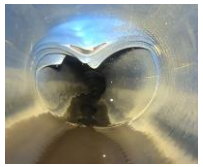
Efficient Calibration of a Laser Dynamic Deflectometer，IEEET INSTRUM MEAS, 2013.

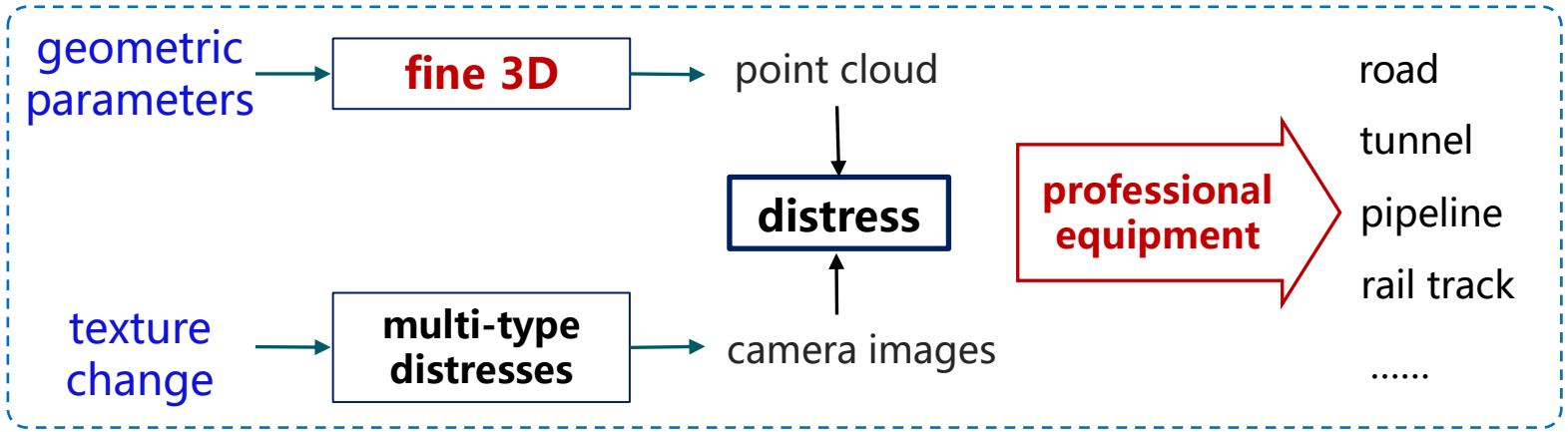
Early Research & Work——surface distress

Surface distress reflects structural or material deterioration.



Requirements : road 7 categories--26 classes || tunnel 10 categories--40 classes || railway 3 categories--30 classes.



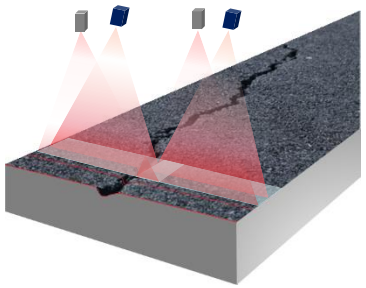


objectives

- **3D point cloud & images**
- **professional equipment**

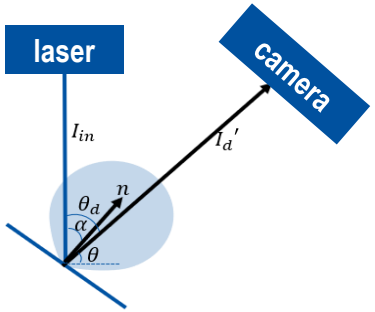
Early Research & Work——surface distress

High-frequency structured light 3D scanner to measure **multi-type surface distresses.**



3D scanning

structured light scanner

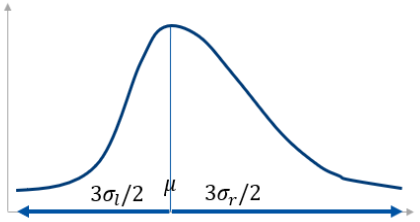


$$I_d' = I_{in}\cos\alpha \cdot k_d \cdot \cos(\theta_d - \alpha)$$

$$I_d = \frac{I_d' \cdot (1+\tan^2\alpha)\tan\theta}{\tan\theta + \tan\alpha}$$

$$\frac{I_d'}{I_d} = \frac{\tan\theta + \tan\alpha}{(1+\tan^2\alpha)\tan\theta}$$

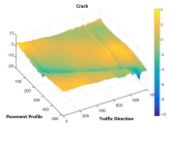
light intensity



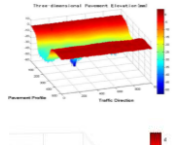
$$\sigma_l^2 = \frac{1}{N_l - 1}\sum_{k=1, x_k<\mu}^{N_l}(x_k - \mu)^2$$

$$\sigma_r^2 = \frac{1}{N_r - 1}\sum_{k=1, x_k>\mu}^{N_r}(x_k - \mu)^2$$

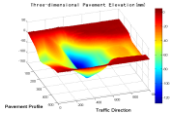
light calibration



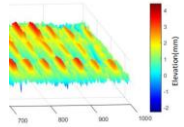
crack



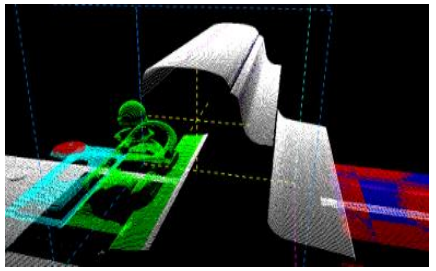
ruts

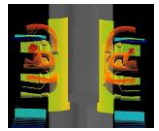


Pit

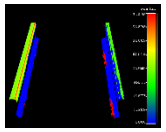


road marks

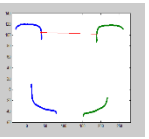




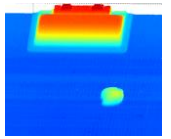
fastener



abrasion



rail section



rail base

Automatic pavement defect detection using 3D laser profiling technology， AUTOMAT CONSTR, 2018.

Early Research & Work——surface distress

Surveying cars for road surface and tunnel wall inspection.

Multi-sensor rail track inspection equipment , which has been applied to urban subway in tens of Chinese cities, and also railways in China and Pakistan.

- Authorized Us/Canada/Australia invention patents: US10571256/CA3021730/AU2016399114.
- Authroized China invented patents: 201430464555.2/ZL200910177893.6

CONTENTS

1 **Background**
- Challenges and Opportunities in Modern Engineering Surveying
- Dynamic and Precise Surveying
- Early Research & Work

2 **Methods**
- Continuous and robust positioning and navigation in mobile and constrained scene
- Rapid sensing of multi-scale and multi-mode spatial information
- Multi-scale modelling and multi-index intepretation of surveyed object

3 **Dams** — Inertial Surveying of Internal Dam Deformation

4 **Bridges** — Vision and IMU Surveying of Long-Span Bridges

5 **Pipelines** — Multi-sensor Robot for Pipeline Surveying

M1 Continuous and robust positioning in mobile and constrained scene

- Proposed **robust positioning** and **scene enhancement** with EOANS (electro-optical aided navigation system), realised **positioning of mm-level** for mobile platform and changing scenes.
- **Provide high-precision and continuous space and time references for mobile platforms.**

open area

no satellite signal

GNSS

LiDAR/vision

odometer

+ **inertial navigation** + **different scenes**

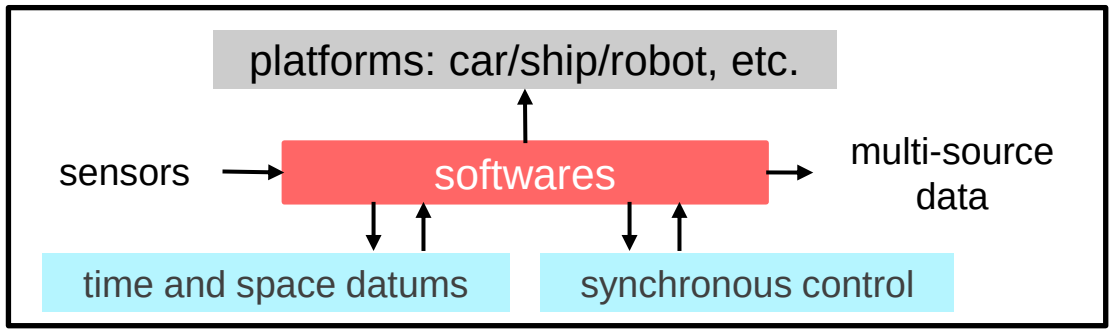
$$P(S_k \mid Z_k) \propto P(Z_k \mid S_k) = exp(\sum_{i=1}^{n} \lambda_i \cdot P(Z_k^i \mid S_k))$$

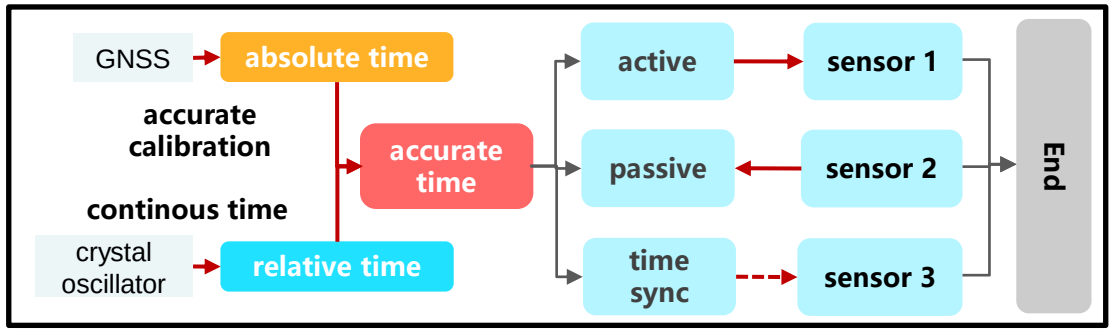
$$P(S_{k-1} \mid S_k) = \frac{1}{\sqrt{2\pi}\sigma_d} e^{-\frac{1}{2\sigma_d^2} d(S_{t-1}, S_t)^2} \cdot \frac{1}{\sqrt{2\pi}\sigma_\theta} e^{-\frac{1}{2\sigma_\theta^2} \theta(S_{t-1}, S_t)^2}$$

attitude measurement method based on factor graph model

M2 Rapid sensing of multi-scale and multi-mode spatial information

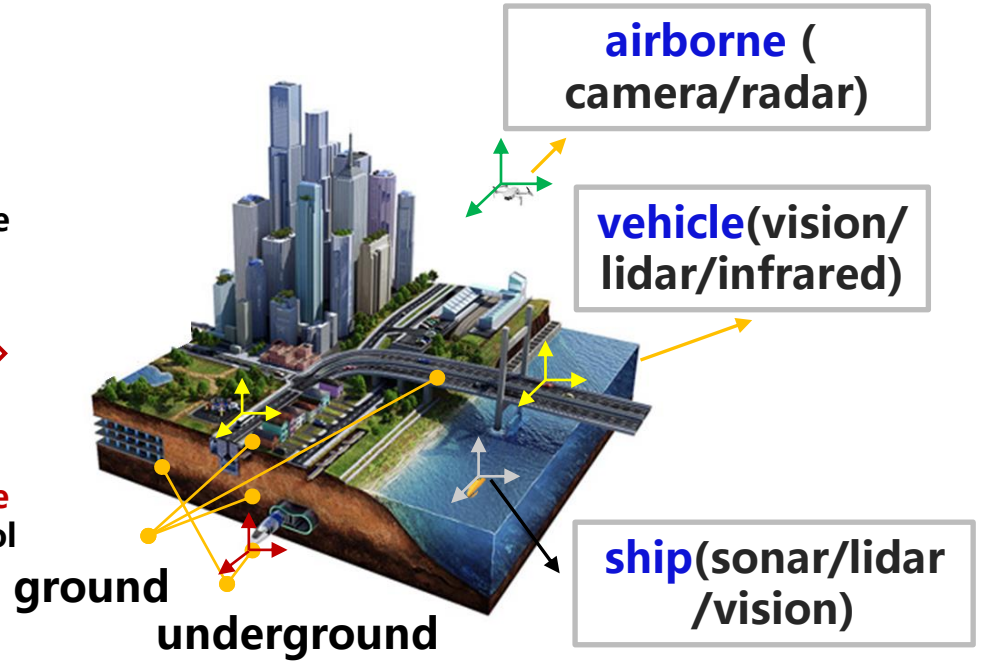
- Invented a multi-sensor integrated synchronous control device, designed a multi-platform unified architecture, and realized efficient and high-precision sensing of multi-platform and multi-scale data.
- **Provide a unified architecture for different platforms.**





cross platform unified architecture

active/passive/time synchronous control

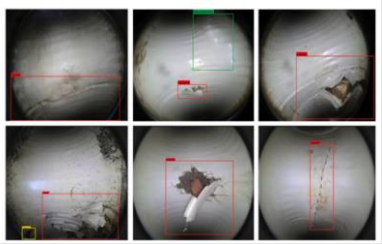


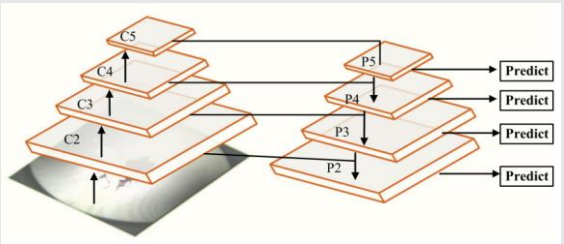
M3 Multi-scale modelling and multi-index intepretation of surveyed object

Combine **priori knowledge** and **multi-scale modelling** to restore **multiple features** of **multi-scale** infrastructure.

data driven

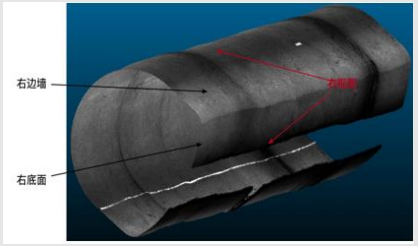
long-tail effect of the training data

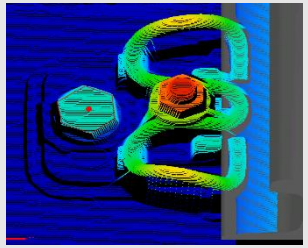


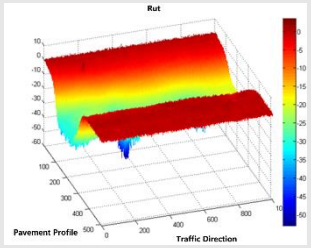


model driven

multi-scale construction objects



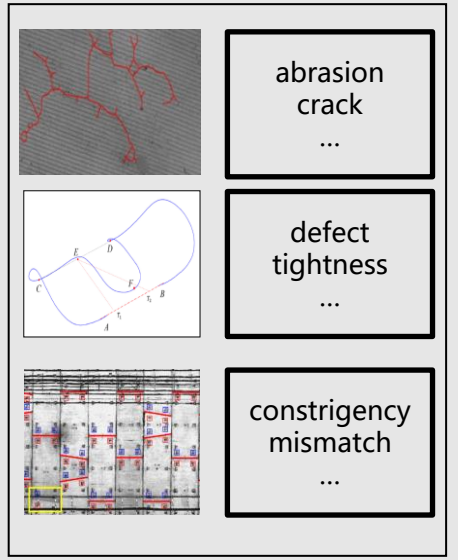




priori knowledge

multi-scale modelling

multi-index intelligent analysis



CONTENTS

1 **Background**
- Challenges and Opportunities in Modern Engineering Surveying
- Dynamic and Precise Surveying
- Early Research & Work

2 **Methods**
- Continuous and robust positioning and navigation in mobile and constrained scene
- Rapid sensing of multi-scale and multi-mode spatial information
- Multi-scale modelling and multi-index intepretation of surveyed object

3 **Dams** — Inertial Surveying of Internal Dam Deformation

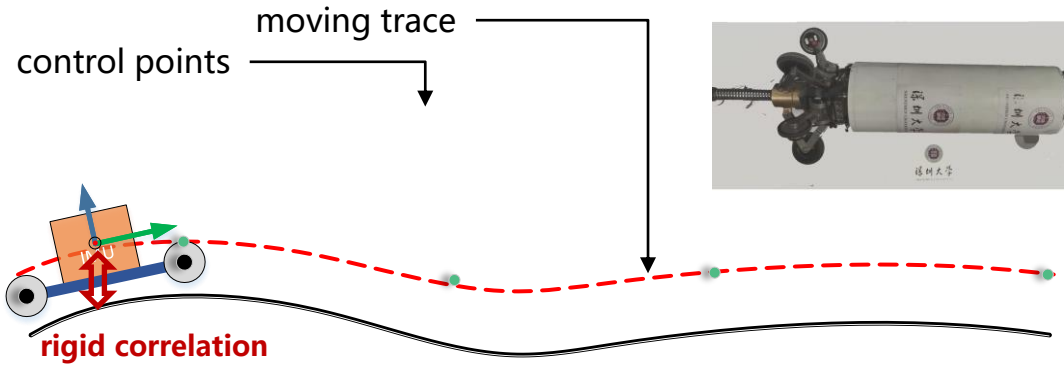
4 **Bridges** — Vision and IMU Surveying of Long-Span Bridges

5 **Pipelines** — Multi-sensor Robot for Pipeline Surveying

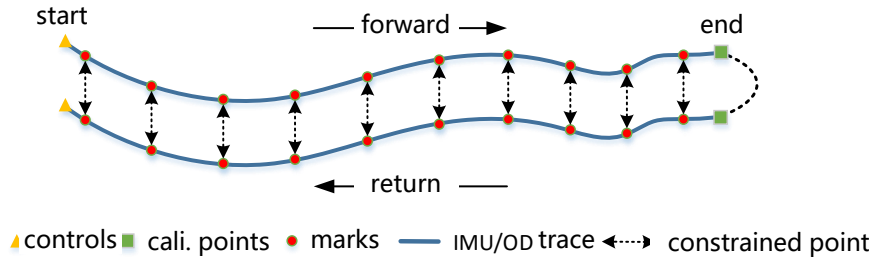
Inertial Surveying of Internal Dam Deformation

- No control point inside the embedded pipe and requires long distance, continusous surveying.
- **Multi-condition constrained inertial surveying** achieves **relative accuracy of 1/100,000**.

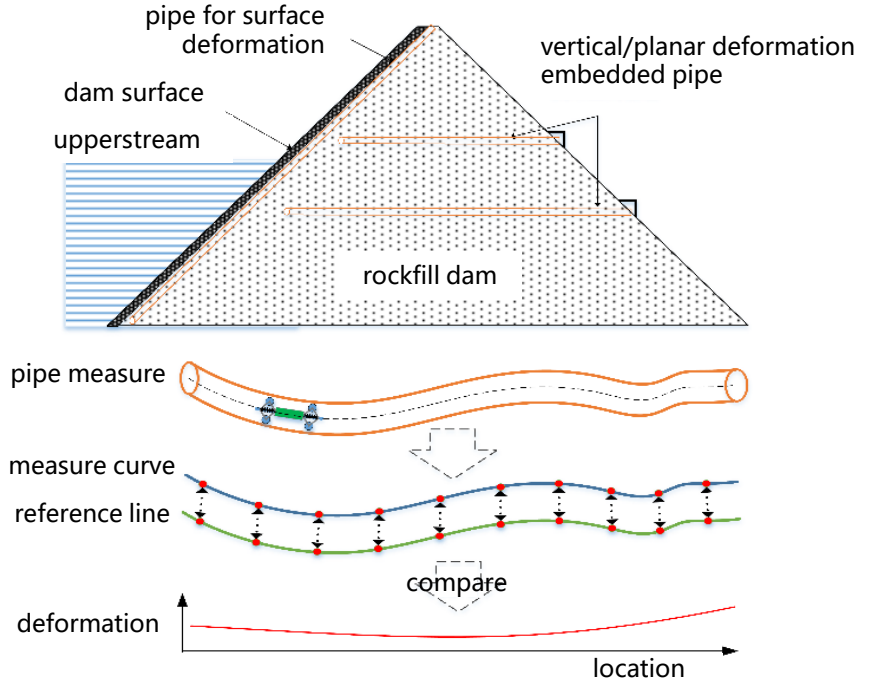
line measuring



factor graph fusion



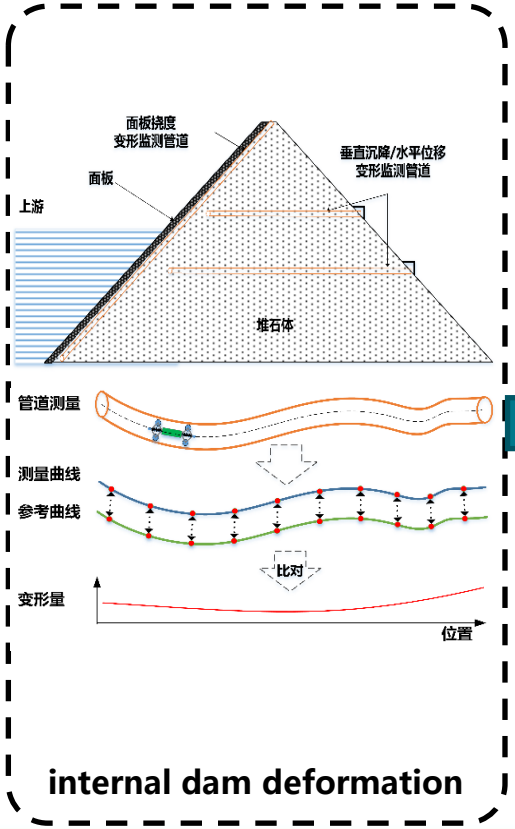
new methods



Internal deformation monitoring for earth-rockfill dam via high-precision flexible pipeline measurements, Automation in Construction, 2022.

Inertial Surveying of Internal Dam Deformation

- **high-precision measuring robot** which inversing the deformation of internal dam by measuring the deformation of the embedded flexible pipe (mm-level precision).
- Lianghekou, Jiayan, Tianchi dams in China, and also used to measure **ice surface flatness** of the **Beijing Winter Olympics speed skating stadium**.



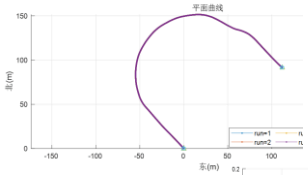
internal dam deformation

the measuring robot

embedded pipe

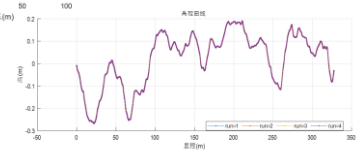
in-situ set-up

periodic measurement

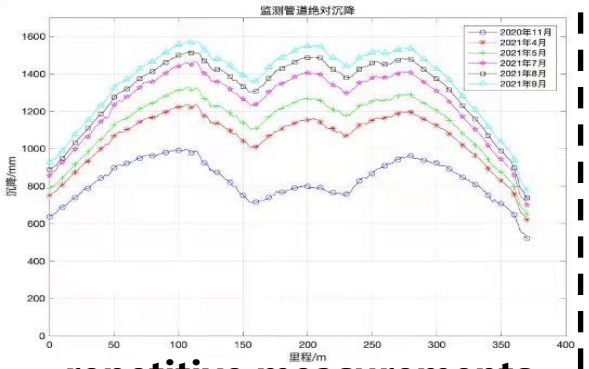


planar

vertical



3D deformation



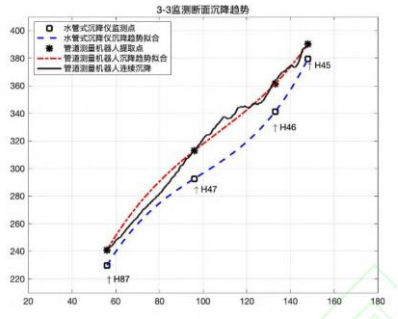
repetitive measurements

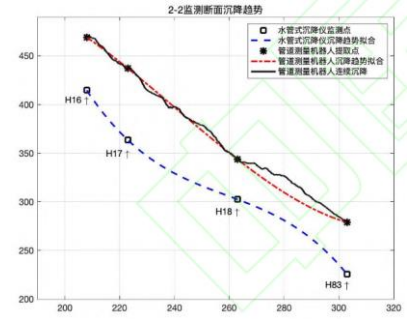
Inertial Surveying of Internal Dam Deformation

- Lianghekou hydropower station has **the highest (265 m) rockfill dam in China,** with long construction period and large deformation.
- The pipeline measuring robot is used to measure the dam deformation, providing a new method for monitoring the internal deformation of large-scale rockfill dams.

Lianghekou hydropower station

field work and deployment





comparison between leveling pipe and robot results

CONTENTS

1 **Background**
- Challenges and Opportunities in Modern Engineering Surveying
- Dynamic and Precise Surveying
- Early Research & Work

2 **Methods**
- Continuous and robust positioning and navigation in mobile and constrained scene
- Rapid sensing of multi-scale and multi-mode spatial information
- Multi-scale modelling and multi-index intepretation of surveyed object

3 **Dams** — Inertial Surveying of Internal Dam Deformation

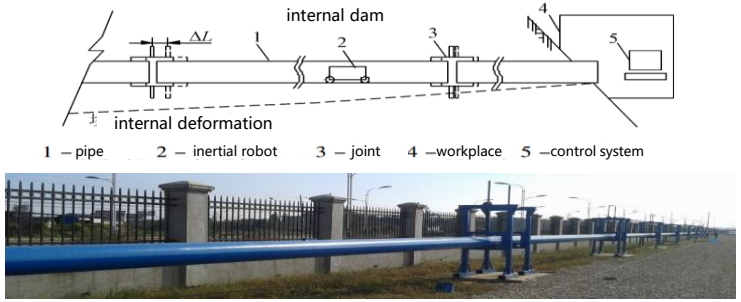
4 **Bridges** — Vision and IMU Surveying of Long-Span Bridges

5 **Pipelines** — Multi-sensor Robot for Pipeline Surveying

Vision and IMU Surveying of Long-Span Bridges

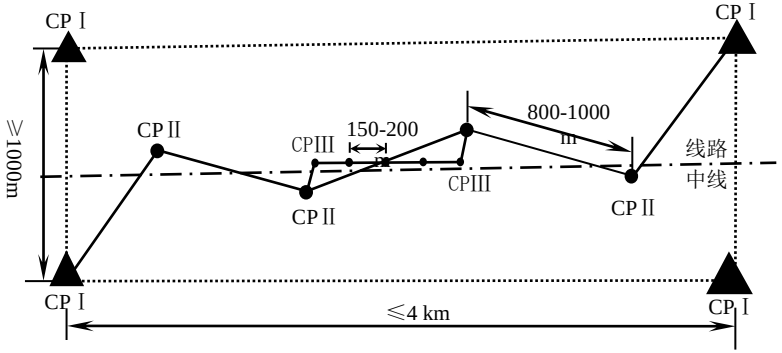
☐ Internal deformation of the rockfill dam

embedded pipe



no control point in closed space

☐ CPIII control network for high speed railway survey



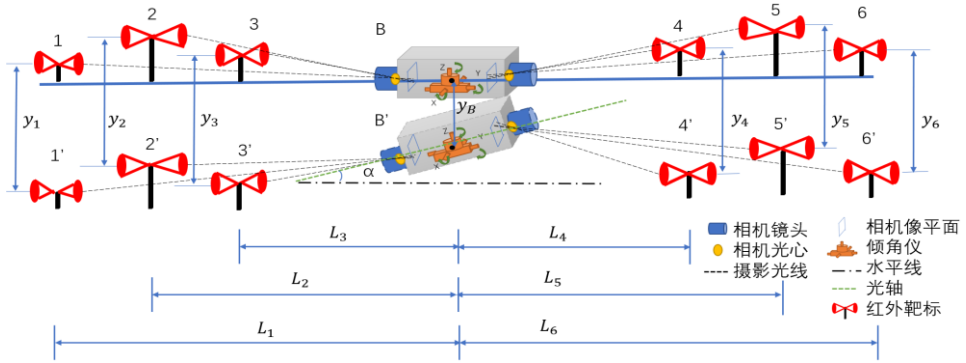
continous monitoring of long-span bridges

control point moves on the bridge

How to achieve high-precision line measurement with no stable control point?

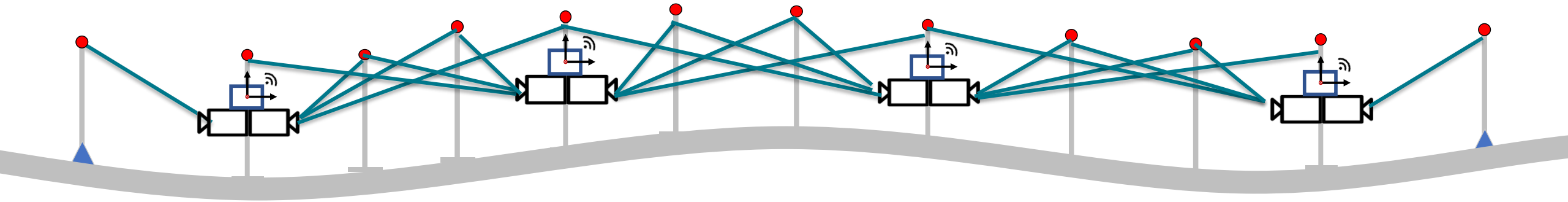
Vision and IMU Surveying of Long-Span Bridges

- Invented **inertial vision sensor** with recursive positioning to achieve dynamic and continuous surveying for a long line structure.
- **Solved the problem that the control point itself is unstable**, and its surveying frequency reaches 30 Hz, and precision reaches mm-level.



$$x - x_0 = -f\frac{a_1(X-X_S)+b_1(Y-Y_S)+c_1(Z-Z_S)}{a_3(X-X_S)+b_3(Y-Y_S)+c_3(Z-Z_S)}$$

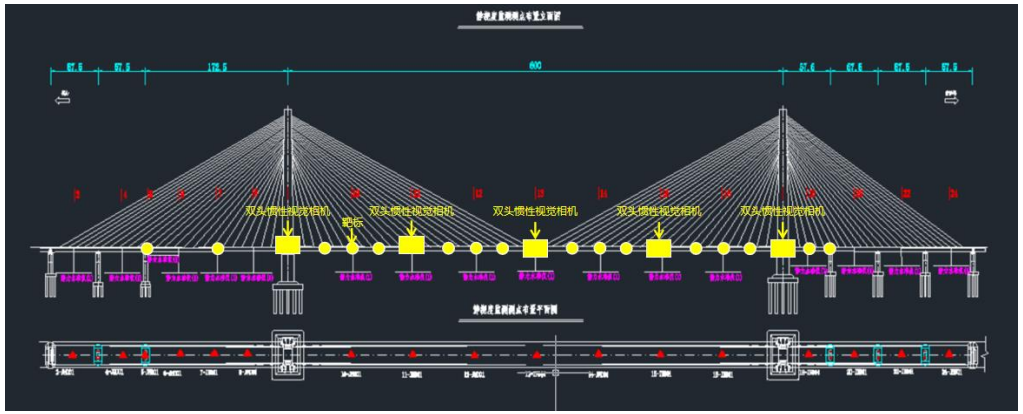
$$y - y_0 = -f\frac{a_2(X-X_S)+b_2(Y-Y_S)+c_2(Z-Z_S)}{a_3(X-X_S)+b_3(Y-Y_S)+c_3(Z-Z_S)}$$

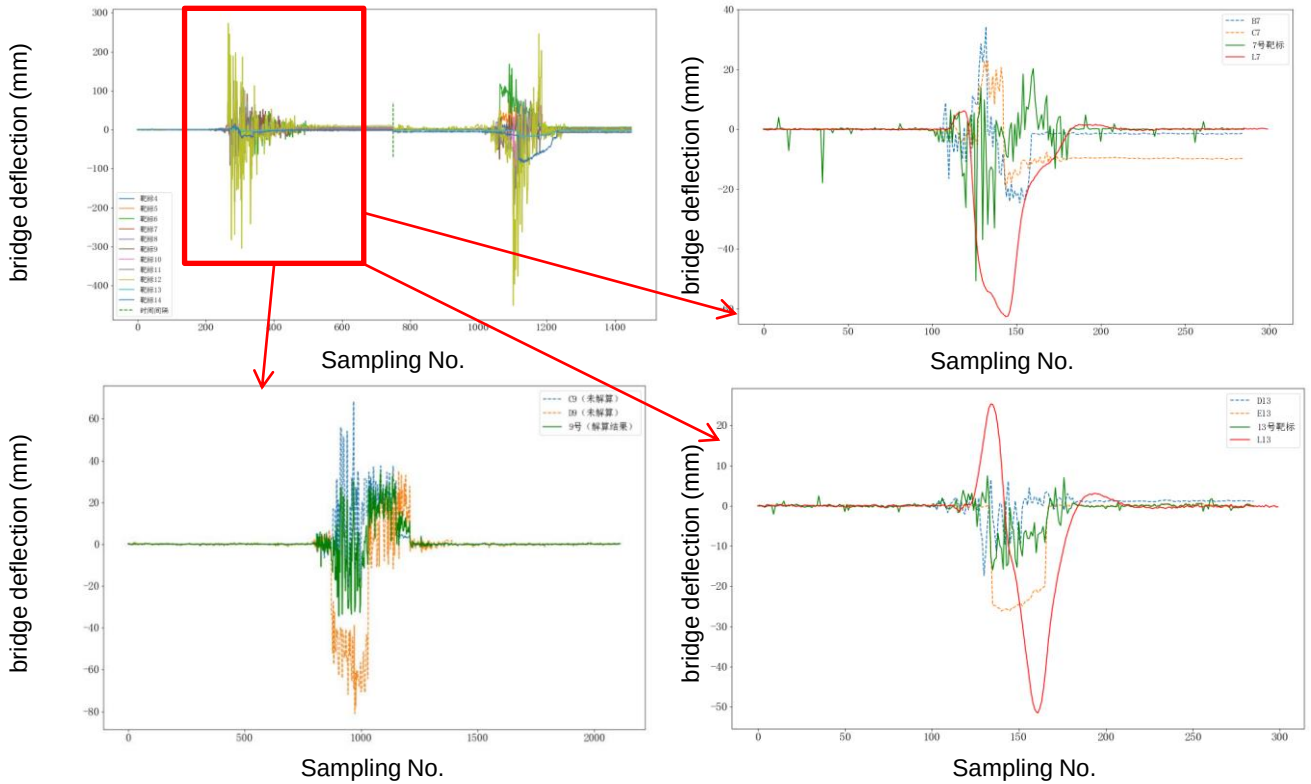


Monitoring the Dynamic Deflection of Bridges using Computer Vision. JOURNAL OF GEOMATICS, 2020.

Vision and IMU Surveying of Long-span Bridges

- Xijiang bridge, Foshan is a long bridge over the Pearl river, with the longest span of 600 meters .
- The vision and IMU surveying system was used to monitoring the real-time linear deformation of the bridge. It well captured the high-frequency displacement of multiple points when the train passed through the brigde.





CONTENTS

1 **Background**
- Challenges and Opportunities in Modern Engineering Surveying
- Dynamic and Precise Surveying
- Early Research & Work

2 **Methods**
- Continuous and robust positioning and navigation in mobile and constrained scene
- Rapid sensing of multi-scale and multi-mode spatial information
- Multi-scale modelling and multi-index intepretation of surveyed object

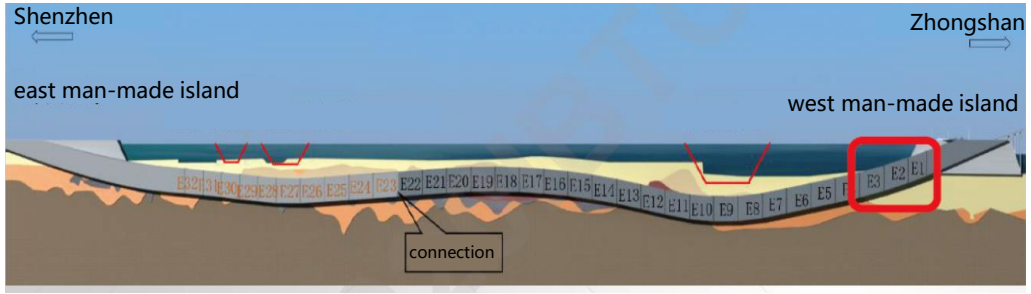
3 **Dams** — Inertial Surveying of Internal Dam Deformation

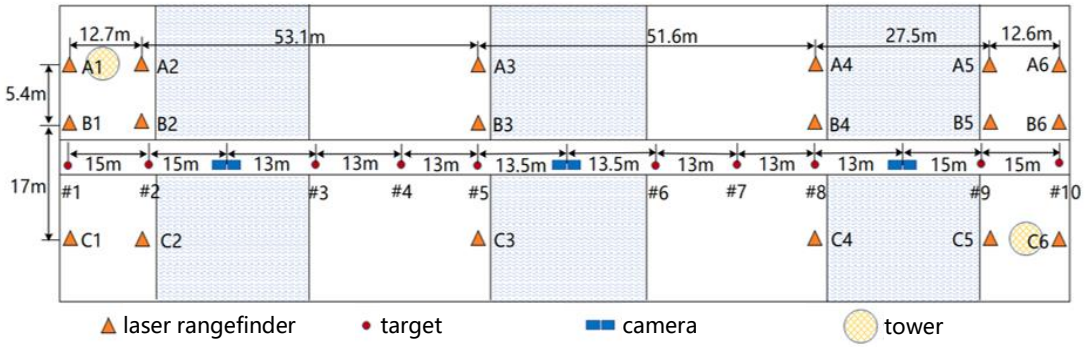
4 **Bridges** — Vision and IMU Surveying of Long-Span Bridges

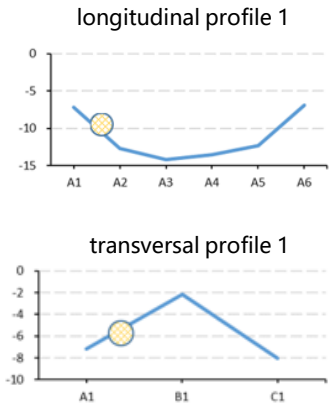
5 **Pipelines** — Multi-sensor Robot for Pipeline Surveying

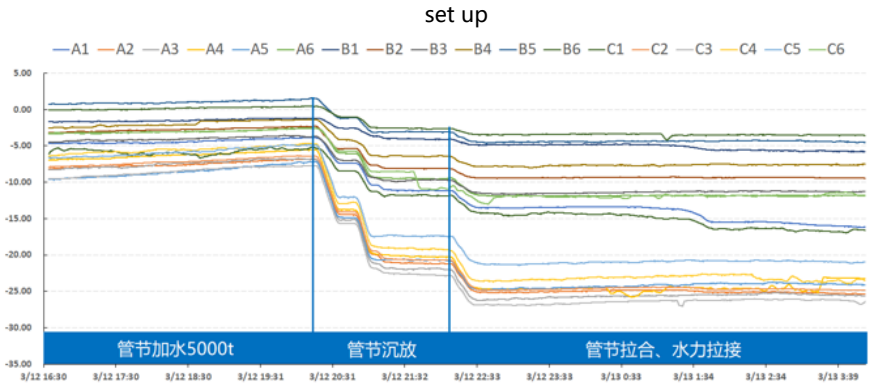
Multi-sensor Robot for Pipeline Surveying

- Deployment of the underwater tunnel is dependent on the surveying tower. The tower itself has a deformation above 3 mm.
- Proposed to survey the deformation of **central line** by using **recursive vision surveying**.



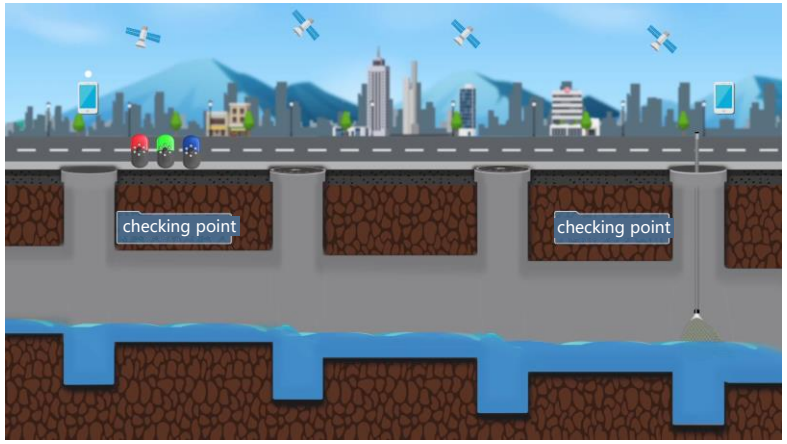


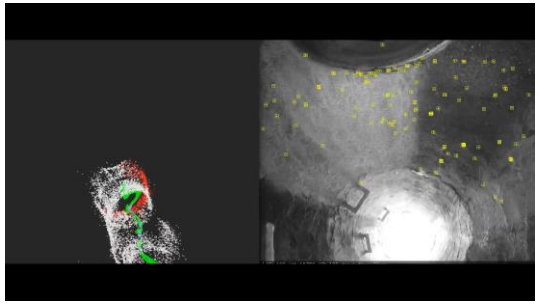


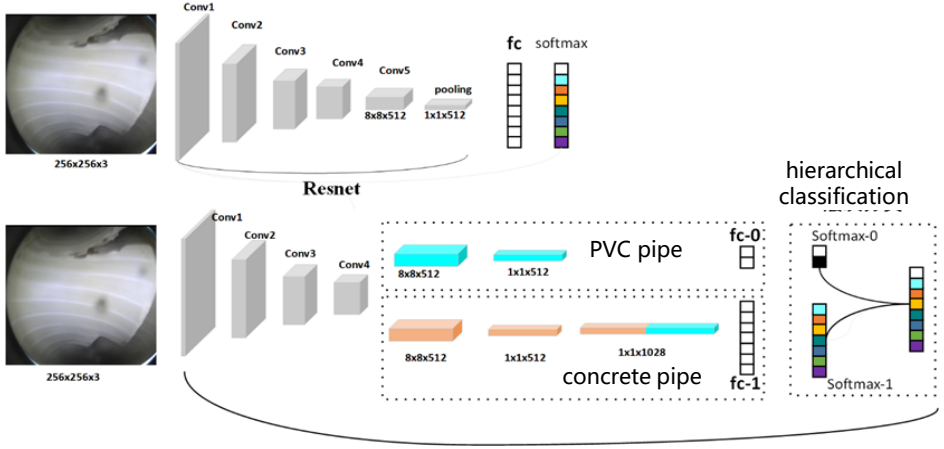


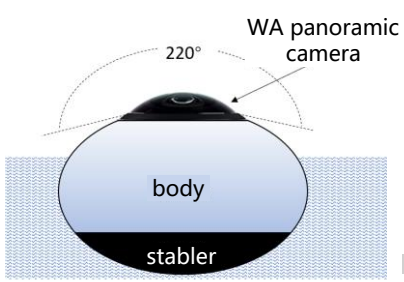
Multi-sensor Robot for Pipeline Surveying

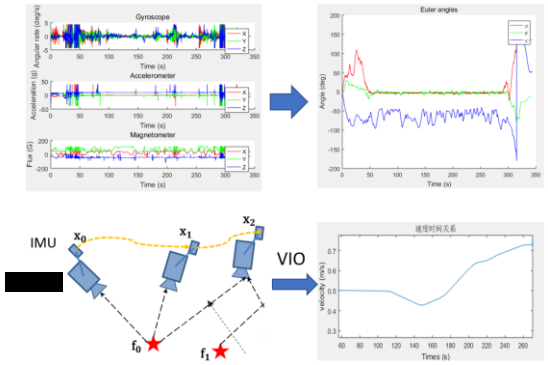
- Invented a **capsular detector** with **camera and IMU**, which can be **drifting on the waterflow** to capture the images inside the drainage pipeline. It has been applied in more than ten cities in China.
- **Deal with the surveying problem when there is water inside the pipeline.**



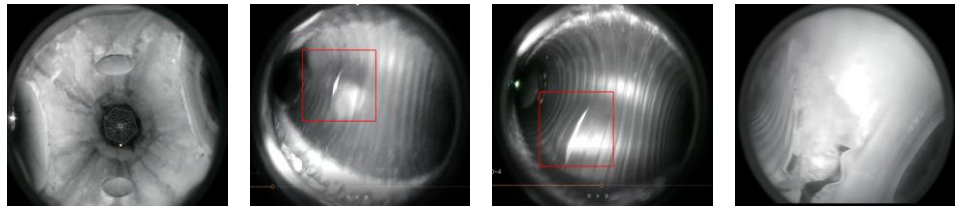








IMU+Visual->Pipeline damage locatoin

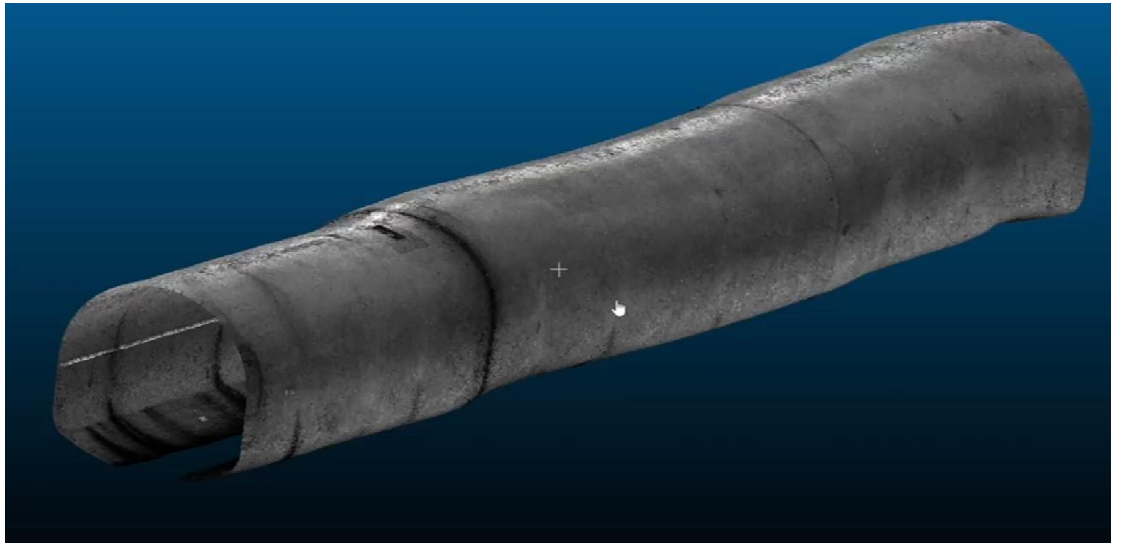


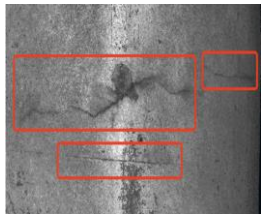
pipe damage detection based on CNN

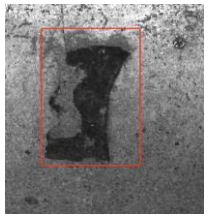
Detection and classification of pipe defects based on pipe-extended feature pyramid network, AUTOMAT CONSTR, 2022.

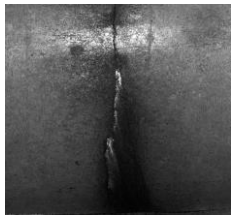
Multi-sensor Robot for Pipeline Surveying

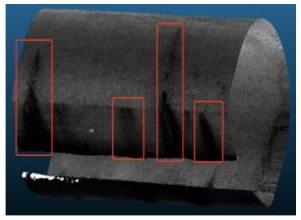
- **Dongjiang water supply project** is an important infrastructure for Hong-Kong's water supply.
- We invented a **Lidar and vision robotic car** for surveying the water pipeline, achieving fine-scale inspection of the pipeline wall distress.

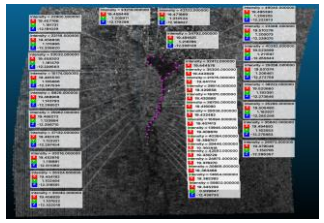






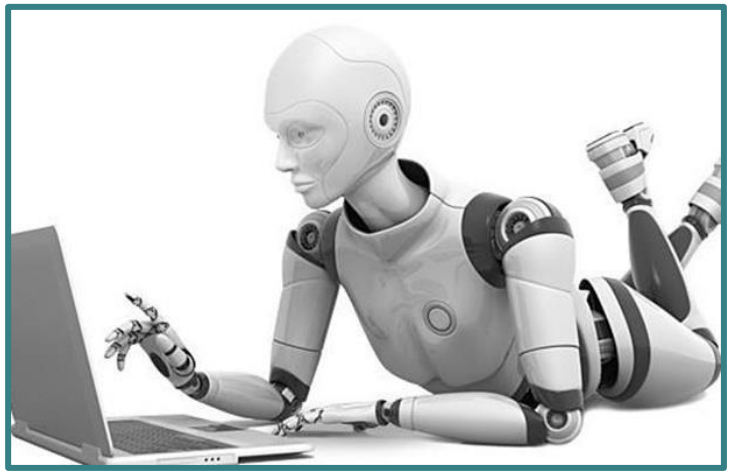






Conclusions

- Engineering surveying supports the **whole lifetime** of engineering projects. Nowadays, it is transferring from **surveying** to **detection and mointoring**, from **geometric parameters** to **multi-index extraction**, from **single-scale** to **multi-scale**.



- Dynamic and precise engineering surveying is one important **interdisciplinary field** and mainly deals with **high-precision multi-index surveying** in **dynamic mode** (moving platforms and changing scenes).

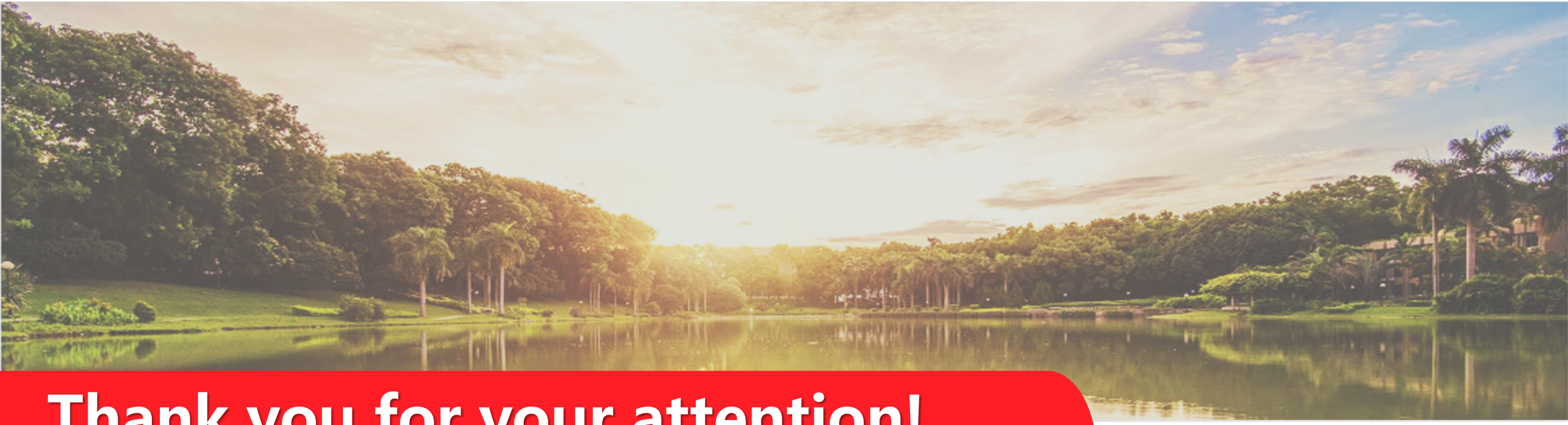
- Surveying requirements in engineering construction are **diverse** and **complex.** The demanding requirement calls for **noval ideas, methods** and **equipments** to deal with the real-scene problems, and to achieve **dynamic, continous and high-precision surveying**.

FIG WARSAW CONGRESS 2022

XXVII FIG CONGRESS

11–15 SEPTEMBER 2022
Warsaw, Poland

Volunteering for the future – Geospatial excellence for a better living



Thank you for your attention! & Welcome to Shenzhen.....

ORGANISED BY FIG SGP

SHENZHEN UNIVERSITY 深圳大学

GUANGMING LABORATORY 光明实验室

PLATINUM SPONSORS esri Trimble