Project number: T21-602/15R

RESEARCH GRANTS COUNCIL
THEME-BASED RESEARCH SCHEME (TRS)

Completion Report on Funded Project

Project start date: 01/01/2016
Project completion date: 31/12/2020

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1. Project Title: Smart Urban Water Supply Systems (Smart UWSS)

2. Names and Academic Affiliations of Project Team Members#

Project team member	Name / Post	Unit / Department / Institution	Average number of hours per week spent on this project in the whole project period
Project Coordinator (PC)	Mohamed S. GHIDAOUI/ Chair Professor	Civil and Environmental Engineering / HKUST	22
Co-Principal Investigator(s)[1]	Pedro J. LEE/ Professor[2]	Civil and Environmental Engineering / University of Canterbury	8

[1] Prof. Joseph H.W. Lee has withdrawn as Co-PI in July 2020.
[2] Prof. Lee was promoted to Professor in late 2017.

	Ross D. MURCH/ Chair Professor	Electronic and Computer Engineering/ HKUST	8
Co-Investigator(s)	Amine BERMAK/ Professor[3]	College of Science and Engineering / Hamad Bin Khalifa University	2
	Bruno BRUNONE/ Professor	Civil and Environmental Engineering / University of Perugia	4
	Ilias G. DIMITRAKOPOULOS / Associate Professor[4]	Civil and Environmental Engineering / HKUST	2
	Huan-Feng DUAN / Associate Professor[5]	Civil and Environmental Engineering / HK PolyU	6
	Bryan W. KARNEY / Professor	Civil Engineering / University of Toronto	6
	Lambros S. KATAFYGIOTIS / Professor	Civil and Environmental Engineering / HKUST	3
	Matthew R. MCKAY / Visiting Professor[6]	Electronic and Computer Engineering / HKUST	4
	Silvia MENICONI / Associate Professor[7]	Civil and Environmental Engineering / University of Perugia	2
	Daniel P. PALOMAR / Professor	Electronic and Computer Engineering / HKUST	4
	Kun XU / Chair Professor	Mathematics / HKUST	6
	Tsih C. YANG/ Professor	Information Science and Electronic Engineering / Zhejiang University	3
	Kamal YOUCEF-TOUMI / Professor	Mechanical Engineering / Massachusetts Institute of Technology	3
	Xin ZHANG / Chair Professor	Mechanical and Aerospace Engineering / HKUST	2
	Yahong R. ZHENG / Professor	Electrical and Computer Engineering / Lehigh University[8]	6
	Jun ZOU / Chair Professor[9]	Mathematics / CUHK	1[10]

[3] Prof. Bermak left his position at HKUST in Nov 2019 and has been working as Professor at the College of Science and Engineering in Hamad Bin Khalifa University

[4] Prof. Dimitrakopoulos was promoted from Assistant Professor to Associate Professor in July 2017.

[5] Prof. Duan was promoted from Assistant Professor to Associate Professor in July 2019.

[6] Prof. McKay was promoted from Associate Professor to Visiting Professor in late 2021.

[7] Prof. Meniconi was promoted to Associate Professor at the University of Perugia in Nov 2016.

[8] Prof. Zheng was promoted to Professor at Lehigh University in Aug 2018.

[9] Prof. Zou was promoted to Chair Professor at CUHK in Aug 2018.

[10] The theoretical issues related to the inversion of low-frequency waves have been largely settled in the earlier stages of the project.

Please highlight the approved changes in the project team composition and quote the date when the RGC granted approval of such changes. For changes in the project team composition, please submit a separate request, together with the justification and the curriculum vitae of the new member(s), to the RGC three months prior to the intended effective date of the change.

3. Project Objectives

Summary of objectives addressed/achieved to-date:

Objectives*	**Percentage achieved**	**Remarks****
1. Advance the understanding of complex physics regarding wave propagation in pipes at the pilot scale to inform and guide the creation of new predictive models for defect detection.	100%	1.1. One key development since the last visit from the Research Grants Council (RGC) two years ago is in regard to the time reversibility (TR) of waves in water supply systems. We provided the first-ever experimental proof that pressure waves in water pipes are time reversible. In a recent "Vision Paper" we analyzed the reasons TR methods are viable even in viscous waveguides and introduced a general criterion to verify their applicability to a given system. 1.2. We performed the first-ever study of TR of waves in pipes in the presence of defects both in the lab and in the field in Hong Kong, Italy, and New Zealand. We developed and experimentally confirmed a closed-form high-frequency-wave (HFW)-leak interaction solution on the basis of the Neumann series. 1.3. We experimentally and theoretically studied pipe-fluid interaction under a wide range of frequencies and found that the viscous behavior of a high-density polyethylene (HDPE) reduces with wave frequency so that at high frequencies (HFs), a viscous HDPE pipe is akin to an elastic one. We also identified the existence of "surface waves" in pipes. At increased frequencies that approach the pipe ring frequency, the wavefront of the water hammer wave is no longer plane but propagates along a small region adjacent to the pipe wall. This knowledge has the potential to be useful in better imaging of defects present in the pipe wall. 1.4. We established theoretically &

Objectives*	Percentage achieved	Remarks**
		experimentally that the signature of defects (e.g., blockages and leaks) is linked to Bragg resonance. 1.5. New insights into the physics of wave-defect interaction have been uncovered for both low frequency (LF) and high frequency (HF) waves, leading to an in-depth understanding of the principles upon which existing methods are based. In addition, the insights are being used to guide the development of new and robust detection methods. 1.6. Simple (impedance-based) models for HF in pipes with different material behaviors have been developed and verified experimentally. 1.7. Initial research has been conducted both experimentally and analytically on the effect of pipe bends on the propagation of HFWs. 1.8. TR has been verified under the most unfavorable conditions that involve a viscous pipe, HFWs, and particularly turbulent flow (Reynolds number, Re ~ 40000). These tests demonstrate the robustness of the method.
2. Develop algorithms and techniques to improve the signal-to-noise ratio from defect reflections.	100%	2.1. A range of super-resolution signal processing tools[11] have been developed and applied to LFWs and HFWs under the presence of white noise. 2.2. An operation that transforms non-Gaussian uncertainty into Gaussian (called noise whitening) has been successfully implemented and is ready to be applied to the noise probability distribution that will be experimentally derived in the next stage of research. 2.3. The noise for LFWs appears to be better represented by the α-stable distribution. Field and lab experiments indicate that α is in the range [1.5, 2.0]. A better understanding of ambient noise assists noise filtering. 2.4. We show that TR-based techniques are optimal in the sense that they maximize signal-to-noise ratio (SNR). That is, the TR

[11] Super-resolution methods can resolve defects smaller than half the probing signal wavelength.

Objectives*	Percentage achieved	Remarks**
		response is the ideal filter to maximize SNR.
3. Establish techniques and technologies to reliably identify and accurately locate system anomalies in a timely manner using either or both low frequency and high frequency waves	100%	3.1. The TR property (proven experimentally in objective 1) was found to form the basis of an efficient, optimal and high-resolution defect detection technique for both LFWs and HFWs. This has been demonstrated both in the lab and in the field in Hong Kong and Italy. 3.2. Using experimental data, we showed that the TR of HFWs identifies leaks and blockages with a resolution of the order of the minimum wavelength of the injected signal. This demonstrates an important premise of the proposal that HFWs can drastically improve defect localization which is a key parameter for water utility operators. 3.3. We showed that filtering using TR in the presence of noise leads to the matched-field processing (MFP) method. MFP-based super-resolution signal processing models for leakage and blockage detection have been developed and tested. The effectiveness of these methods to identify both single and multiple defects has been verified. The models have now been extended to detect leakage in a viscoelastic pipe. 3.4. We successfully applied the TR-based techniques to analyze field data from Ngau Tau Kok (NTK), Hong Kong and Trento, Italy. We secured projects from the Drainage Services Department (DSD) and RGC to further test the TR techniques. Moreover, we have successfully tested the techniques on The Hong Kong University of Science and Technology (HKUST) campus' water supply system. 3.5. Data fusion from different sensors was shown to improve detection even under strong noise and other modeling uncertainties. 3.6. The super-resolution methods have been tested using data from the Water Engineering Laboratory at the University of Perugia as well as data from HKUST. We

Objectives*	Percentage achieved	Remarks**
		found that the proposed technique significantly outperforms existing methods and is able to accurately identify even small leaks in a noisy environment. 3.7. The super-resolution methods were extended to a branched system and have been tested using data from a newly built branched-pipe system at HKUST. 3.8. A framework based on hypothesis testing which not only identifies defects, but also provides information on the probability of detection as well as the probability of false alarms was developed. 3.9. A physics-informed machine learning-based classification technique to determine the existence of defects was formulated and validated numerically and experimentally. 3.10. Inverse techniques for dealing with model parameter uncertainty have been developed. 3.11. In order to cope with the ill-posedness in leakage detection problems, Tikhonov regularization, along with the generalized cross validation (GCV) and L-curve methods for determining the regularization parameters have been proposed. 3.12. Using TR, direct time-domain inversion techniques for blockage in single, multiple, and branched pipe(s) have been developed. 3.13. An area reconstruction technique for blockage in arbitrary shapes has been successfully tested analytically, numerically, and experimentally. This technique can be applied to multiple-pipe systems. 3.14. The TR-based highly promising area reconstruction technique was extended to leaks and discrete blockages. 3.15. A TR-based model for leakage detection using HFWs has been derived and tested experimentally. 3.16. A Bayesian inversion scheme using a Markov chain Monte Carlo approach to estimate water pipeline dimensional and material parameters (pipeline inner radius, thickness and density, and longitudinal and transverse wave speeds of the pipeline wall material) based on the waveguide's

Objectives*	Percentage achieved	Remarks**
		dispersion characteristics has been successfully formulated and tested.
4. Build a theoretical foundation for in-pipe communication using acoustic waves in the presence of flow	100%	4.1. A signal model for a pipeline channel consisting of straight elastic pipelines with quiescent water has been developed. Experiments to verify the model for steel and HDPE pipe materials were performed. Noise and interference in pipelines in the laboratory environment were measured. With few adjustments, the same model is also applicable to pipes with flow. 4.2. The effect of pipeline wall thickness and flanges on signal propagation has been investigated. In addition, the damping effect of junctions to the propagation of HFWs has been identified. 4.3. Wave behavior in a non-rigid pipe was experimentally investigated. Models to explain the experimental observations have been developed. These include both the pressure and pipe wall displacements as a response to an injected signal. 4.4. Models have been developed to characterize acoustic noise in water pipelines. These models are based on results from experiments in the laboratory and the field. They show that pipeline noise can be characterized by sources with Gaussian and α-stable probability distribution functions. 4.5. A communication system based on an adaptive subcarrier orthogonal frequency-division multiplexing (OFDM) approach was proposed. The communication system adapts the utilized subcarriers based on knowledge of the cut-off structure of the guided acoustic waves. Enhanced performance compared to conventional approaches has been shown.
5. Design and develop test beds to explore, refine and prove the new technologies, including both laboratory facilities and field test programs	100%	5.1. Laboratory facilities have been built at HKUST. These facilities are easily adaptable to the research needs of the project. A field-scale test bed was constructed at Beacon Hill Reservoir (in collaboration with the Water Supplies Department (WSD)). The field experimental facility was completed in October 2017 and the first phase of experiments on system

Objectives*	Percentage achieved	Remarks**
		characterization and experimental protocol development with transient tests has been completed. A real-world live lab involving part of the water supply system in NTK, Hong Kong, has also been used to test our defect detection techniques. 5.2. A remotely controlled cloud-based platform that allows monitoring and diagnosis of the water supply system and the application of our novel TR-based techniques has been developed. A pilot implementation of the system has been installed at the HKUST campus and involves four fully synchronized base stations, whose functions are controlled via an interactive web application. This development constitutes an important step towards the commercialization of time reversal-based techniques and technologies. 5.3. Seven new access points for HFW-based methods were designed and are now fully operational at the BH facility. 5.4. A range of laboratory tests for HFWs have been developed and proven to be instrumental in the testing of the TR of HFWs. 5.5. A series of tests were performed on a transmission line in Yuen Long, Hong Kong and confirmed the presence of leaks. This success has resulted in interest from WSD to expand this program. As a result, we are currently developing a new test site on a main transmission line located along Ching Yau Road, Yuen Long. This transmission line of 1.3 km in length and comprises of a mild steel pipe 1400 mm in diameter. It supplies treated water from the water treatment work to the Ngau Tam Mei Fresh Water Primary Service Reservoir. 5.6. Following a collaboration with Hong Kong DSD, we have expanded the application of our TR technologies to three sewage rising main systems (namely in Penny’s Bay pump station, Chum Hum Kok Road, and Chum Hum Kok beach) with promising results. 5.7. Two field tests were also conducted in Italy. The first one is conducted on a

Objectives*	**Percentage achieved**	**Remarks****
		transmission line in Trento, Italy. This pipe system comprises a main pipe that has a total length exceeding 1,322 m and a diameter of 506.6 mm. Several branches with different material (some are steel, and others are high-density polyethylene (HDPE)) are connected to the main. A leak has been successfully detected and localized along one of the HDPE branches. The second field test is conducted on a transmission line in Trieste, Italy. The pipeline is an iron pipe with 1.3m in diameter and about 19 km long conveying about 750 L/s of water.

* *Please highlight the approved changes in objectives and quote the date when the RGC granted approval of such changes.*

****** *Please provide reasons for significantly slower rate of progress than originally planned.*

6. Research Highlights and Outputs

6.1 What are the most exciting research accomplishments of the project?

(Please list five or more of the team's best research accomplishments, such as journal and conference papers, software codes, research infrastructure, etc. For each item, please clearly justify how it has achieved international excellence (e.g., best paper award, invited presentation, citations, product licensed to industry, etc.))

Our TRS project "Smart Urban Water Supply Systems" (Smart UWSS) (i) advanced the understanding of high- and low-frequency wave propagation in UWSS, (ii) pioneered the use of time reversal (TR), including providing experimental proof, (iii) developed novel TR-based techniques for defect detection in pipes, (iv) established 11 testbeds (4 laboratory-scale set-ups and 7 real-world sites), (v) created an automatic real-time system for defect detection at LF and HF as well as a distributed data acquisition system that would enable the monitoring and diagnosis of large-scale water supply networks, and (vi) developed novel channel signal models for water pipes. RGC's Monitoring and Assessment panel noted that "*the team introduced time reversibility, a new technique…[and] built up impressive installations for the field experiments both in Hong Kong and in Italy.*" The panel found the work to be "*highly interdisciplinary, adopting some of the best ideas in civil engineering, fluid mechanics, wireless communication, and physics,*" rating the overall progress as "*exemplary*" and project coordination as "*excellent.*" Below, we succinctly summarize our most exciting research accomplishments.

i. **We pioneered the application of time reversal (TR) in UWSS by establishing the first experimental proof of TR in this field and subsequently developing novel TR-based techniques for defect detection in pipes.** We are delighted that our pioneering TR work was noted by the RGC monitoring panel as they commented after their visit in October 2019 "*the team introduced 'time reversibility,' a new technique in the past two years.*" Indeed, being the first to recognize, prove and apply TR of pressure waves in pipes is undoubtedly the pinnacle outcome of the project. What makes this even more remarkable is the fact that waves in pipes are highly dispersive, subject to a myriad of damping sources and propagate in highly dynamic and turbulent media as well as in a pipe system with complex topology. We tested the TR in both elastic and viscoelastic pipe systems with lengths ranging from 6 m to 5,000 m, diameters ranging from 50 mm to 700 mm and involving a myriad of complexities such as junctions, branches, connections to buildings, curvatures, and dynamic devices such as pumps and pressure relief valves. The TR has been successfully proven over frequencies ranging from about 1 Hz to 100 kHz and has formed the foundation of all the new defect detection techniques developed in this project. This pioneering TR work has been well received by and garnering much attention from the hydraulics community as evidenced by the frequent requests to deliver keynote and invited talks on this topic (see Addendum VII) and by the recent "Vision Paper" that will soon appear. In this "Vision Paper", we provide theoretical and practical reasoning to convincingly argue that TR is poised to have tremendous impact not just in UWSS, but in all branches of hydraulic engineering. A TR-based leak detection US patent (Patent No.: US 11,162,867 B2; See Addendum X) has already been granted and two more patents are currently under preparation.

ii. **We substantially advanced the state-of-the-art understanding of high- and low-frequency wave propagation in UWSS.** We proved the un-expected but important result that visco-elastic pipes behave elastically at high frequencies (HF). We derived an analytical mapping between damped and undamped signals, which resulted in far better resolution than had previously been attained. We provided the experimental support for this important finding. We derived the first-ever, closed-form solution for HF waves for a wide range of defects and tested them numerically and experimentally. We provided the first proof that noise follows an alpha distribution and becomes Gaussian at a high Reynolds number — a result that is central to defect detection in pipes. We designed optimal input signals that enhance range and minimize uncertainty in the estimated parameters. We extended Cauchy's theorem to tree networks and proved the existence of Bragg resonance in pipes. Cauchy's boundary theorem states that a wave field in any complex domain can be reconstructed from knowledge of the pressure and velocity field at the boundary of this domain. A related theorem exists for tree networks in the absence of a loop. It states that the structure and parameters including defects of a connected tree network with no loops, regardless of complexity, are uniquely identifiable provided that the pressure and velocity at all vertices are measured. Our group relaxed the requirements of this theorem by showing that velocity measurements are not required and that only pressure measurements are needed at *N-1* vertices in a tree network with *N* vertices provided that we employ time reversal for the reconstruction. This is an important result because pressure measurements are straightforward and do not require access to the fluid (water). An analogy is the straightforward measurement of blood pressure! On the other hand, existing technologies for velocity measurements are intrusive, involve a great deal of uncertainty and require far more accessibility than is often practical in UWSS.

iii. **We established 11 unique testbeds (4 laboratory-scale set-ups and 7 real-world, field, test sites).** We are delighted that the RGC's Monitoring and Assessment panel noted that our team has "*built up impressive installations for the field experiments both in Hong Kong and in Italy.*" The testbeds cover a wide range of scales, materials, and complexities. Indeed, the pipe systems' length scales ranged from 100 m to 10 km and their diameters ranged from 75 mm to 500 mm. Materials ranged from elastic to visco-elastic pipes and from metallic to non-metallic. The complexity ranged from simple lines to networks with multiple dynamic devices and flow controls, such as pressure vessels, multi-stage pumps, pressure relief valves, air valves and fire hydrants. For example, the site in Yuen Long (Hong Kong) is a steel transmission main that is about 500 m long and 700 mm in diameter. The system involves pumps, air-vent valves, hydrants, and a number of connections. In addition, the real-world pipe system in Trento, Italy, comprises a main pipe that has a total length exceeding 1,322 m and a diameter of 506.6 mm. The system comprises a pump and several branches, while the main pipe is partly steel and partly high-density polyethylene (HDPE). These unique systems have and will continue to be a source of fundamental and practical knowledge on waves and their usage for defect detection and overall system diagnosis.

iv. **We developed innovative, robust, and reliable TR-based techniques for the diagnosis of UWSS.** The TR techniques have been extensively tested in our test beds. We showed that they are computationally efficient and achieve the resolution limit set by the physics of wave diffraction. In addition, the TR-based methods are applicable to various types of defects including leaks, bursts, pipe wall thinning, discrete and extended blockages, entrapped air pockets, unauthorized connections, etc. Moreover, the TR methodology was found to be far superior to all existing methods when applied to real water distribution systems (e.g., in Ngau Tau Kok (NTK) as well as Yuen Long in Hong Kong). Using TR techniques, we performed the first-ever defect localization using HFWs. The TR techniques allowed us to meet a key premise of this project, namely that the combination of low-frequency waves (LFWs) and high-frequency waves (HFWs) is essential for accurately localize defects. In fact, our experimental (lab and field) and theoretical work confirms that the resolution of LFWs is of the order of tens of meters while that of HFWs is far higher—of the order of centimeters.

v. **We developed the first automatic real-time system for defect detection at LF and HF as well as a distributed data acquisition system that enables the monitoring and diagnosis of large-scale water supply networks.** The system employs a suite of different methods (that are all TR-based) to capture pressure signals and use it to estimate the location of leaks and other defects in the system without human intervention. This is all done in matter of seconds. The system comprises of data acquisition and control base stations, that are synchronized to high accuracy and controlled via an interactive web application. The user has the ability to monitor the system and conduct tests on demand. Finally, the base stations are powered with solar panels; thus are self-reliant and can be installed at remote locations where access to the electric grid is limited. We view this system as the first foray towards the commercialization of our technology. We are working with the water supplies department (WSD) to implement this system in a transmission line along Ching Yau Road, Yuen Long. This latest field setup is a transmission mild steel pipeline that is 1.3 km long and has diameter of 1400 mm. Its function is to supply treated water from the water treatment work to the Ngau Tam Mei Fresh Water Primary Service Reservoir.

vi. **We developed channel signal models for water pipes that incorporate the channel noise and interference, as well as approaches for estimating the key parameters required in detecting pipe defects and enhancing their accuracy.** We have proposed the use of subcarrier delay spread-based adaptive orthogonal frequency-division multiplexing (OFDM) for communication through wideband waveguide channels, such as water pipeline channels. The technique has important communication applications where robots or vehicles travel inside waveguide channels such as tunnels or water pipelines. We studied noise over a wide range of frequencies both in the lab and field and determined their probability distribution. A key result is that noise becomes more Gaussian in real water systems allowing the TR methods as well as many other available techniques to be adapted. In particular, we are able to integrate the signal, noise, interference, probing and estimation techniques within the TR methods.

6.2 What was the added value of the TRS funding, rather than standard project grant funding? *(For example, could this work have been achieved with other funding scheme, such as the General Research Fund or Collaborative Research Fund? If not, why?)*

This TRS allowed us to assemble an internationally recognized, cross-disciplinary research team to conduct frontier Smart UWSS research in close partnership with the WSD and the AcegasApsAmga SpA in Italy. RGC's Monitoring and Assessment panel commented: "*This is a large, coherent, and top-notch team carrying out work at the highest level on an important urban problem…The project team comprise a group of distinguished researchers locally and internationally. Their work is highly interdisciplinary, adopting some of the best ideas in civil engineering, fluid mechanics, wireless communication, and physics. The team has built up impressive installations for the field experiments both in Hong Kong and in Italy.*" The findings from this TRS project enable the timely detection of UWSS defects and formulation of proactive mitigation measures, which will crucially contribute to the sustainable development of HK through water conservation. This TRS project makes important and long-lasting contributions to **Theme 2: Developing a Sustainable Environment** as well as **Theme 4: Advancing Emerging Research and Innovations Important to Hong Kong.**

6.3 If the project has not met its original objectives, why?

All the objectives have been successfully met.

6.4 (a) Peer-reviewed journal publication(s) arising directly from this project:
(Please attach a copy of the publication and/or the letter of acceptance if not yet submitted in the previous progress report(s). All listed publications must acknowledge RGC's funding support by quoting the specific grant reference. Please mark the symbol "#" next to the publications involving inter-institutional collaborations)

Please refer to Addendum I.

(b) Recognized international conference(s) in which paper(s) related to this project was/were delivered:
(Please attach a copy of each conference abstract)

Please refer to Addendum II.

(c) RGC funding should have been acknowledged in all publication(s)/conference papers listed in (a) and (b) above. If no acknowledgement has been made in any of the publications/ papers, please indicate and provide explanations.

All the publications/ papers have acknowledgement.

6.5 To what extent this project has strengthened inter-institutional collaborations and other partnerships?

Strong and proven collaborations between team members and water industry partners have been developed, leading to the pioneering research advances and to the plethora of testing beds that are succinctly summarized in section 6.1 of this report. We are delighted that this fact was noted by the RGC monitoring panel as they wrote "*The project team has established closed collaborations with University of Perugia in Italy and other groups internationally. The larger scale field sites in Trento and Milan, Italy, provide longer pipe lengths than the local network for the team to compare the results with their theoretical computation. The team has also built up strong relationship with the Hong Kong Water Supplies Department (WSD) as can be evidenced by the presence of the Deputy Commissioner and several of its senior and knowledgeable staff during the review. The review team members are satisfied with the collaboration—very well* *done [on] both [the] domestic and international [fronts].*"

The pioneering research work that was accomplished in this TRS could not have been possible without the strong collaboration, support and input from members of the internationally recognized and cross-disciplinary research team as well as advisory board members. This fact was not lost on the RGC panel as they found our work to be "*highly interdisciplinary, adopting some of the best ideas in civil engineering, fluid mechanics, wireless communication, and physics.*" We are proud to report that the strong collaboration and partnership developed in this TRS has since been extended to include pioneers in TR, metamaterials, super-resolution, artificial intelligence, in-pipe sensor and robotic technologies, inverse mathematics as well as inventors of TR technologies (e.g., Echosens, Supersonic-Imagine, Cardiawave, GreenerWave), and industry members from leading water professionals in HK, Italy, Canada, and UK. This expanded partnership led to (i) new research funding and additional field sites for the Smart UWSS technology (see section 7.1 below) and (ii) strong support for the renewal proposal that was submitted in September 2021; the proposed project has been shortlisted for full proposal submission (see letters of support from water industry in HK, Italy, UK, and Canada in Addendum IX).

6.6 Research students trained (registration/awards):

Please refer to Addendum III.

6.7 Specific products (e.g. software or netware, instruments or equipment developed):

i. As stated in section 6.1, we developed the first automatic real-time system for defect detection at LF and HF as well as a distributed data acquisition system that would enable the monitoring and diagnosis of large-scale water supply networks. Leveraging GPS technologies, the system comprises base stations that are synchronized to an accuracy of the order of 10^{-5} s (Fig. 1c). The acquired data are uploaded to a cloud server and processed using our novel technologies to evaluate the health of the water supply network. The system differs from existing passive measuring systems in two key aspects: (a) each base station controls an electro-valve that produces pressure waves, and (b) the sampling rate is much higher and ranges from 1kHz to 50kHz. The system is fully controlled through a newly developed web application (Fig. 1a), and the user can conduct tests on demand. Moreover, each station is self-reliant and powered with solar panel arrays (Fig. 1b). Hence, the stations can also be installed in remote areas where grid electricity is not available. This system is being tested on the HKUST campus, the water supply system in collaboration with WSD and the drainage system in collaboration with Drainage Services Department (DSD). We will also test the system at the Airport Authority Hong Kong in March 2022. These tests will pave the way for the product's eventual commercialization.

ii. Our team designed and constructed special controllable valves (see Figs. 1d and e) that are able to generate clean (i.e., minimum noise) and repeatable impulses, which can be used to experimentally obtain the response function of a pipe system and to implement the TR technique. Moreover, a special valve (Fig. 1f) was developed to simulate bursts and leaks for high-frequency test setups and to demonstrate TR theory. The valves in Figs. 1d and e are controlled by an in-house developed code.

iii. The codes that underpin the automatic real-time system were all developed in-house. In addition, members of the SUWSS project have coded numerous algorithms, such as numerical pressure wave propagation solvers, physics-informed machine learning processors, waveguide dispersion solvers, etc.

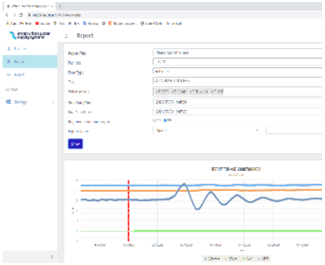

Fig. 1a

Fig. 1b

Fig. 1c

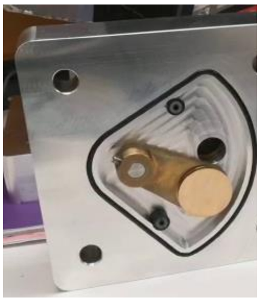

Fig 1d

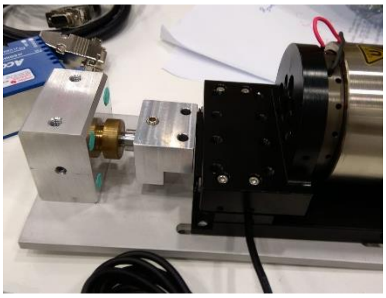

Fig 1e

Fig 1f

6.8 Other education activities and/or training programs developed:

Please refer to Addendum IV.

6.9 Please highlight any deliverables indicated in the project implementation timetable endorsed by the RGC which have not been covered or achieved as per sections 6.1 to 6.8 above, and explain/ elaborate.

None.

<u>Project Management</u>

6.10 Please elaborate how the PC has played his/her role in coordinating and managing the project.

RGC's Monitoring and Assessment panel wrote: "*This is a large, coherent, and top-notch team carrying out work at the highest level on an important urban problem…The project team comprise a group of distinguished researchers locally and internationally. Their work is highly interdisciplinary, adopting some of the best ideas in civil engineering, fluid mechanics, wireless communication, and physics. The team has built up impressive installations for the field experiments both in Hong Kong and in Italy. The review team should give the PC an excellent rating on this aspect.*"

Please refer to Addendum VI.

7. Awards and Recognition

7.1 Have any research grants been awarded that are directly attributable to the results obtained from this project?

Please refer to Addendum XII.

7.2 Have any project team members participated as invited speakers in or organizers of international conferences as a result of this project?

Over 25 keynote and invited lectures were delivered, showing significant interest in the time reversal work and its application in water supply systems as well as other water-related problems, including tsunamis, rogue waves, climate change, river hydraulics etc. (Please refer to Addendum VII for details). In this regard, the RGC panel wrote "*The project team members have gained recognition internationally, as can be seen by the talks given at top conferences and publications at leading journals in a variety of disciplines. Job well don*e!"

7.3 Have any project team members taken leadership positions in editorial boards, scientific and professional organizations?

Please refer to Addendum VIII.

7.4 Any documentary proof of the application of technologies arising directly from this project?

A TR-based leak detection US patent (Patent No.: US 11,162,867 B2; See Addendum X) has already been granted. Two more patents are currently under preparation. One is called "Time-reversal technique for defect detection in pressurized pipelines" and the other is called "Defect detection in pressurized pipelines using time reversal of high frequency waves". (See Addendum X).

We successfully applied the TR technique in the field in HK and Italy. In collaboration with WSD, we developed two unique test beds in HK, and we are currently developing a third one in Ching Yau Road, Yuen Long, NT. In collaboration with our team members from University of Perugia, we tested our technology in water transmission lines in Trento, Italy. Real leaks, air blockages, unknown dynamic devices and side branches were identified.

We received funding from HKUST to apply the techniques developed in this TRS project to the water supply network on the university's Clear Water Bay campus. This facility has been instrumental in the development of the TR-based automatic-real time system. Moreover, the pilot facility has been used as an educational platform for our students and the university community over the past two years. In addition, we organized several facilities visits for various stakeholders such as WSD, DSD, Hong Kong Science and Technology Parks Corporation (HKSTP), Gammon Construction Limited, Airport Authority Hong Kong, Hong Kong Radio, and our university leadership team. The facility was also presented via Zoom in a number of international talks that were delivered by the PI. Such field demonstrations have paved the way for the uptake of this home-grown technology. For example, we are planning to jointly test the Smart UWSS technology with the Airport Authority Hong Kong on the water supply system at the airport. The technologies resulting from our Smart UWSS project are already making impact beyond the water supply domain and into other public utility systems in HK. For example, we received funding from DSD to diagnose parts of their pressurized sewerage system. To date, we have successfully localized a real leak location on Chum Hom Kok road in Stanley and detected a malfunctioning air valve in the Penny's Bay pump system. We have also successfully implemented the technology in Chum Hom Kok beach station and demonstrated that simulated leaks as small as $0.05\ \mathrm{l\ s^{-1}}$ can be detected and localized. Finally, we designed access points for the TR technology in a cooling seawater system that belongs to HKSTP.

7.5 Other awards and recognitions as a result of this project (please specify):

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8. Impacts

8.1 What are the current and expected impacts of the project on the long-term development of Hong Kong (social or economic development, e.g. patent, technology transfer, collaboration with external organizations, etc.)?

In HK, water loss stands at 15% (150 million cubic meters per year), resulting in over HK$800 million/year in financial losses and creating a significant carbon footprint (water supply is the 3rd largest energy user in HK). The global volume of water loss is around 129 billion m^3/per year, which is enough to supply 130 cities like HK. The direct cost of water loss amounts to more than US$39 billion/year, and the energy used to treat, transport, and pump water is staggering. The novel TR techniques, new insights, improved models, and refined designs arising from this research have set the foundation for the **Smart UWSS**, poised to save an enormous amount water, energy and cost.

i. We are already making an important impact on the water industry in HK. In their 2019 visit, RGC's Monitoring and Assessment panel noted that the "*technology deployment in the field appears to have real world impact.*" Our collaboration with WSD led to the implementation of the TR technology in Ngau Tau Kok and Yuen Long. We received a HK$1.3 million grant to develop the world's first real-time LF-TR system for HKUST's water supply and fire sprinkler networks. We provided advice on the development of the Anderson Road Quarry site into a pilot smart city area. We have been using our field and lab testing facilities to engage leading consultancy firms and government departments such as DSD, HKSTP, Gammon, Black & Veatch, AECOM, and China Gas, and our project has been picked up by the local radio. These engagements are already bearing fruit. We received a HK$1.4 million grant from DSD to use LF-TR to detect leaks in sewerage lines in Penny's Bay, Chung Hom Kok and Deep Water Bay's pressurized sewerage systems in HK. We recently implemented 24 LF access points at the seawater district cooling system in Tseung Kwan O Industrial Estate owned by HKSTP. These examples clearly show that the research is transferrable to applications beyond UWSS.

ii. A US Patent (Patent No.: US 11,162,867 B2) has already been granted. Two more are being prepared.

iii. We engaged students and alumni in the Technology Start-up Support Scheme for

Universities (TSSSU) and with start-up businesses.

iv. The generated knowledge, technology and human capacity are already establishing a world-class reputation for HK in the field of Smart Cities.

v. We built strong collaboration with the water industry in Hong Kong, Italy, UK, and Canada, all of which have expressed strong support and desire to collaborate on future TR-based projects (see Addendum IX).

vi. We joined efforts with the Pipebots project in the UK, where we organized a Smart UWSS-Pipebots workshop in December 2020 and are currently conducting joint research. The PI of Pipebots is a Co-PI in our application for the TRS project renewal.

vii. Water supply systems are expanding at exponential rates with about 100 km of pipes being added each year in HK, and over 40,000 km of pipes (8 times the length of all water pipes in HK!) being installed each year in the mainland. Worldwide, millions of kilometers of urban water infrastructure will need to be added to supply populations in cities, which are expected to grow globally by 2.5 billion in 2050. Pipe replacement and rehabilitation are regular practices in all UWSS. For example, HK has recently completed the replacement of about 4,000 km of pipes (half of its UWSS). It is estimated that the U.S. will need to invest about US$110 billion per year in water infrastructure over the next 20 years (Biden's administration announced plans to invest over US$45 billion to replace the lead pipelines). Such vast and large-scale system expansion, replacement and rehabilitation programs will offer ideal opportunities to integrate TR-based technologies within UWSS.

viii. In the long term, we envision that TR-based technologies will transform UWSS practice in a manner similar to how ultrasound transformed medicine.

In the medium to long term, this TRS project, as well as the research and projects that will result from it in HK and elsewhere will:

1) Assist HK in (i) meeting its 2030 UWSS water-loss-reduction, climate action plan 2030+, WIN (water intelligent network) vision, and 2050 net-zero targets and (ii) developing environmental services as a pillar industry.
2) Assist mainland China in meeting its 2030 "Three Red Lines" water limits and 2060 net-zero targets.
3) Create Sustainable & Smart UWSS of the future that are resource efficient and resilient.

8.2 Others (please specify):

i. We trained 19 PhDs, 6 MPhils, 13 Postdoctoral fellows/ Research Assistants, 31 Master's of engineering students, 24 final year project students, and over 30 high school students.

ii. The generated knowledge, technology and human capacity are already establishing a world-class reputation for HK in the field of Smart Cities.

iii. The fundamental knowledge and engineering science developed in this project have been published in 126 *Journal Papers (19 of them are under preparation and 3 of them are under review),* 55 *Conference Papers, and* 62 *Theses and Reports.*

iv. We developed strong collaboration with international and local stakeholders, please refer to Addendum V for more details.

9. Sustainability of the Project

9.1 Whether there are new ideas evolved directly from this project?

TR has transformed fields such as medicine, ocean acoustics, seismology and telecommunications and led to the creation of successful spinoff companies, such as Echosens, Sensitive Object, Supersonic Imaging, TR Communications, Cardiawave, and GreenerWave. Due to the strong foundation established in this TRS project, the field of UWSS is now firmly at the “foothills” of its own TR-based transformation. Our goal now is to advance the science and engineering and create a TR UWSS transformation that parallels those accomplished in other areas. This, in turn, requires a fundamental change in the way UWSS are designed and built. Fortunately, this fundamental change is underway! We are transforming the new 6.5-km potable water supply network on our HKUST Guangzhou (HKUST-GZ) campus into the world’s first fully accessible living UWSS lab for imaging. The pipes are 200 to 300 mm in diameter and are composed of ductile iron pipes arranged in loops. The system is designed to deliver a peak flow of nearly 11,945 m^3/d, serving about 13,000 consumers. A similar transformation is planned for the newly opened and well-instrumented Q-leak system owned by our partner, WSD. Building information models (BIM) have been developed for both systems. Ports for insertion and extraction of in-water sensors and robots have been designed and are currently being tested at our existing Beacon Hill test bed, and will be installed in the HKUST-GZ and Q-leak systems in the summer of 2022.

The HKUST-GZ and Q-leak systems will allow us to examine the fidelity of TR to turbulence and other hydrodynamic instabilities; dissipation; flow unsteadiness; multi-scattering at junctions, bends, water-pipe-soil interfaces, air cavities; and random forcing (e.g., demands and device vibration). In addition, these systems will allow us to explore and harness TR’s unique property of turning medium complexity, reverberation, and multipath waves into outcomes with improved image resolution. Encouraged by our proof-of-concept results, we will also study and exploit the use of internal pipe-lining made of metamaterials without altering the host-pipe as well as physics-informed machine learning models for the significant enhancement of TR imaging.

9.2 Whether there are new projects evolved directly from this project?

A renewal TRS project entitled “Time Reversal Imaging for Sustainable & Smart Urban Water Supply Systems” has been submitted in September 2021 and was shortlisted for full proposal submission. Its mission is to leverage and build upon our previous TRS to develop the engineering science required to (i) create the TR imaging technology for Sustainable & Smart UWSS of the future that are resource efficient, resilient and free from costly and fatal failures and (ii) assist HK in meeting its water and energy commitments and in developing environmental services as a pillar industry. The specific goals are (i) to understand time reversibility of acoustic waves in a turbulent, dissipative, unsteady flow in a complex network of pipes with numerous dynamic devices and subjected to reverberation, multiple scattering and random forcing, and to develop strategies and transformations to compensate for processes that break space reciprocity and time reversal symmetry; (ii) to develop theories, strategies and techniques to enhance TR imaging by introducing resonators/metamaterial structures without altering the flow capacity and strength of the host-pipe; (iii) to establish fundamental theories that compensate for signal damping from energy losses in the fluid, pipe and surrounding media so as to sharpen the TR images; (v) To deploy, test and further develop existing and emerging technologies, including the in-pipe sensor and robotic systems developed by team members; and (vi) to develop physics-constrained, machine learning, signal-processing techniques for pipe imaging. The expected deliverables and benefits include an imaging system founded upon TR theory; metamaterial concepts and physics-informed machine learning for UWSS; and fully functional pilot HKUST-GZ and the Q-leak systems to help create the blueprint for **Sustainable & Smart UWSS** of the future. The findings will assist HK in its 2050 carbon neutral mission and its 2030 water loss reduction from UWSS via locally developed innovation and technology founded upon the proposed research. As an important side benefit, the HKUST-GZ and Q-leak will allow integration of other technological developments into UWSS and will become home to other water and energy research in HK.

In November 2021 a proposal entitled "Exploring subwavelength resonance in water hammer" was submitted under the General Research Fund Scheme. This proposed project seeks to make the TR technique super-resolving by using metamaterial concepts. The aim is to employ analytical, numerical, and experimental methodologies to address the following questions: what are the effects of steady, unsteady and visco-elastic damping, flow, and normal modes on our ability to control and manipulate Waterhammer waves using metamaterials? To what extent does experimental evidence corroborate with the potential suggested by our proof-of-concept results? This research will result in an order of magnitude increase in the range and resolution of the TR techniques that have been developed in the TRS project.

Our 1-3 years plans: We will expand our testing programs with our partners WSD, DSD and AcegasApsAmga SpA. We will develop new testing sites for HKAA and HKSTP as well as in the UK and Canada, together with Fido and HydraTek. We will establish the first two phases of the HKUST-GZ and Q-leak systems and will expand our advisory board to include more water industry experts and leaders in green technology and environmental businesses. We will continue to engage all stakeholder groups—water professionals, students, government authorities and the public—through technical and non-technical seminars, meetings, and field demonstrations of the TR technology.
Our 4-10 years: Completion of the HKUST-GZ and Q-leak systems in the 4th year of the project and the development of the fully automated TR imaging technology will secure buy-in from water professionals and will pave the way for the uptake of the technology in HK and the Greater Bay Area, Padua, and Trento in Italy and in other cities that we will identify with our collaborators and partners from France, Switzerland, UK, Canada, Qatar, and USA. Fido tech wrote "*are happy to offer access for your technology to some of our field trials with a water company in the UK*". In addition, the President & Director of HydraTek & Associates in Canada wrote "*HydraTek has very well-established connections with relevant client organizations (municipalities) that may be interested in learning about, and potentially piloting, the tools and technologies being developed such that dialogues can be facilitated to this end"* and concluded by stating *"we are very hopeful that your proposal is successful and look forward to the realization of the advancements proposed as well as the opportunity to collaborate on this interesting and exciting projec*t." Such expansions to other cities around the world will position HK as a world leader in **Sustainable & Smart UWSS** and promote development of high value-added environmental services industries.
Beyond 10 years—regular expansion, replacement, and rehabilitation of UWSS to provide huge market and potential for implementing the TR technology across the

globe. Water supply systems are expanding at exponential rates, with about 100 km of pipes being added each year in HK alone, and over 40,000 km of pipes (8 times the length of all water pipes in HK!) being installed each year in the mainland. Worldwide, millions of kilometers of urban water infrastructure will need to be added to supply populations in cities, which are expected to grow globally by 2.5 billion in 2050. Pipe replacement and rehabilitation are regular practices in all UWSS. For example, HK has recently completed the replacement of about 4,000 km of pipes (half of its UWSS). It is estimated that the U.S. will need to invest about US$110 billion per year in water infrastructure over the next 20 years (Biden's administration announced plans to invest over US$ 45 billion to replace the lead pipelines). We intentionally included young rising stars in our team to ensure that the research, development and human building capacity will continue long into the future. We envision that TR imaging will transform UWSS practice in a manner similar to how ultrasound transformed medicine.

9.3 Whether there are new collaborations developed directly from this project?

The excellent results and progress made in this TRS provided the strong foundation for our renewal TRS proposal which we submitted in September 2021 which has just been shortlisted for full proposal. It aims to develop the engineering science required to (i) create the TR imaging technology for **Sustainable & Smart UWSS** of the future that are resource efficient, resilient and free from costly and fatal failures and (ii) assist HK in meeting its water and energy commitments and in developing environmental services as a pillar industry. In this renewal project our internationally-recognized and cross-disciplinary research team has been extended to include pioneers in TR, metamaterial, super-resolution, artificial intelligence, in-pipe sensor and robotic technologies, and inverse mathematics as well as inventors of TR technologies (e.g., Echosens, Supersonic-Imagine, Cardiawave, GreenerWave). The already-secured support from leading water professionals in HK and Italy has been also extended to Canada and UK. The success and reputation that has been built during this TRS, the importance of the problem being addressed and the scientific, engineering and technological challenges and opportunities facilitated the formation of the new partnerships.

The newly added academics are:

i. **Prof M. Fink** (Link: https://www.institut-langevin.espci.fr/mathias_fink?lang=en) is the pioneer of TR physics and used TR to transform fields, such as medicine, ocean acoustics, seismology, and telecommunications. He is also an inventor and entrepreneur who created successful spinoff companies, such as Echosens, Sensitive Object, Supersonic Imaging, TR Communications, Cardiawave, and GreenerWave.

ii. **Profs C.T. Chan** (Link: http://www.phys.ust.hk/ctchan) and J. Li (Link: http://jensenli.people.ust.hk/) made fundamental breakthroughs in the field of acoustic metamaterials. For example, the foundational *Science* paper entitled "Locally Resonant Sonic Materials" published in 2000 stands at over 4,000 citations.

iii. **Prof K. Horoshenkov** (Link: https://www.sheffield.ac.uk/mecheng/people/academic/kirill-v-horoshenkov) leads the large-scale "Pipebots" project in the UK, which aims to revolutionize buried pipe infrastructure management with the development of micro-robots (7.2M pounds). We aim to integrate our TR methodology with their micro-robots.

iv. **Prof H. Ammari** (Link: https://people.math.ethz.ch/~hammari/), F. Triki (Link:

https://membres-ljk.imag.fr/Faouzi.Triki/) and H. Zhang (Link: https://facultyprofiles.hkust.edu.hk/profiles.php?profile=hai-zhang-haizhang) are world leaders in inverse mathematics, TR and super-resolution. They provide the mathematical underpinning of the research.

v. **Prof Y. Wang** (Link: https://facultyprofiles.hkust.edu.hk/profiles.php?profile=yang-wang-yangwang) is a renowned expert in artificial intelligence who will be instrumental in the development of physics-assisted machine learning models for UWSS.

vi. **Prof X. Wang** (Link: https://orcid.org/0000-0002-1156-3840) is an expert in TR-based defect detection and with whom we have a large number of publications in this field. The fact that he is based in Beijing will help ensure timely uptake of the technology in the capital city.

vii. **Prof L. Zhou** (Link: https://orcid.org/0000-0002-1750-6126) is an expert in pipeline hydraulics and defect detection. He has built an impressive pipeline experimental facility at his university that will be used to further test and showcase the TR technology. The fact that he is based in Hohai will greatly facilitate the timely uptake of the technology in the region.

viii. **Prof G. Ma** (Link: https://research.hkbu.edu.hk/researcher/guancong-ma)is an expert in TR and metamaterials. He has, in a short time, conducted pioneering research that was published in *Science* and *Nature*.

ix. **Prof S. Li** (Link: https://lisen1990.wixsite.com/senli) is an expert in optimization and a rising star. His involvement will greatly help in TR imaging.

x. **Prof J. Zhao** (Link: http://jzhao.people.ust.hk/group.html) is a renowned expert in soil mechanics. His involvement is necessary for understanding wave radiation from fluid to pipe to the surrounding soil.

xi. **Prof. F Shi** (Link: https://mae.hkust.edu.hk/en/people/faculty/detail/fan-shi) is an expert in acoustics, nondestructive evaluation (NDE), ultrasonic material characterisation, advanced ultrasonic imaging, numerical modeling of elastic waves and metamaterials.

The following water companies have provided strong letters of support to our research (see Addendum IX):

i. Fabian Papa & Partners HydraTek Inc., Ontario, Canada
ii. AcegasApsAmga S.p.A., Italy
iii. Airport Authority (AA) Hong Kong.
iv. FIDO Tech Ltd, United Kingdom
v. Drainage Services Department (DSD), Hong Kong
vi. Water Supplies Department (WSD), Hong Kong

9.4 Please give details on how much money and from which sources has been obtained/requested for the specific purpose of continuing the work started under this project.

Prof. Ghidaoui has obtained three GRFs from RGC, totaling HK$2,255,721, including:

1. Blockages in Water Pipes: Theoretical and Experimental Study of Wave-blockage Interaction and Detection (HKD$875,000; project no. 16203417)
2. Theoretical and Experimental Investigation of the Interaction between a Leak and

3D Waves in Pipes (HKD$632,421; project no. 16208618)

3. Pipeline Hydraulics: Resolving the Paradox of Time Reversibility in Damped Transients (HKD$748,300; project no. 16214219)

He has also submitted a TRS extension project entitled "Time Reversal Imaging for Sustainable & Smart Urban Water Supply Systems" (Project Ref No.: T21-604/22-W; Requested amount: HK$69.5 million) and a GRF entitled "Exploring subwavelength resonance in waterhammer" (Project Ref No.: 16211522; Requested amount: HK$1,605,990).

10. Statistics on Research Outputs

(Please ensure the statistics in this section are consistent with the information presented in other sections of this report.)

<table>
<tr><th rowspan="2"></th><th rowspan="2">Peer-reviewed journal publications</th><th rowspan="2">Conference papers</th><th rowspan="2">Scholarly, books, monographs and chapters</th><th rowspan="2">Patents awarded</th><th colspan="2">Other research outputs (please specify)</th></tr>
<tr><th>Type</th><th>No.</th></tr>
<tr><td rowspan="4">No. of outputs arising directly from this research project</td><td rowspan="4">126*</td><td rowspan="4">55</td><td rowspan="4">1 book ("Beginning Fluid Mechanics" Textbook in preparation)</td><td rowspan="4">1 Patent granted (2 Patents in preparation)</td><td>PhD/Mphil Thesis</td><td>19</td></tr>
<tr><td>Master Project Reports</td><td>17</td></tr>
<tr><td>Final Year Project Reports</td><td>24</td></tr>
<tr><td>Engineering Reports</td><td>2</td></tr>
</table>

**19 of them are under preparation and 3 of them are under review.*

11. Public Access of Completion Report

(PCs of projects funded in 2010/11 academic year or onwards are required to release the completion reports to the public through the RGC website. Completion reports containing information such as abstracts in non-technical terms, objectives, research output including the list of conference papers / publications / journals and research findings and contact information of PCs should be open to public access.)

Please specify the information, if any, that cannot be provided for public access and give the reasons.

Information that cannot be provided for public access	Reasons

12. The Layman's Summary

(describe in layman's language the abstracts and research impact of the project.)

We have assembled an internationally recognized, cross-disciplinary research team to conduct research in close collaboration with the Water Supplies Department (WSD) of HK. Our findings will enable the timely detection of UWSS defects and formulation of proactive mitigation measures, which will crucially contribute to the sustainable development of HK through water conservation.

Urban Water Supply Systems (UWSS) are vital, large, long-lived, complex, largely inaccessible, and aging, fraught with deficiencies and inefficiencies that result in massive water loss and energy use. Thus, UWSS present an enormous challenge to making cities sustainable, adaptive and carbon neutral. The World Bank estimates the monetary value of lost water worldwide to be about US$39 billion/year. Pipe failures can paralyze businesses and cause devastating urban floods. Worldwide, UWSS are challenged by urban growth and climate change. Yet, current methods to diagnose leakages and defects in complex underground UWSS remain highly inadequate.

Our TRS project (**Smart UWSS**) pioneered the use of time reversal (TR) and developed novel TR techniques for defect detection in UWSS. TR involves an experimental step where water-borne waves propagating at high speed (km/s) are sensed, and a theoretical step where the chronological order of the sensed waves is reversed and reemitted into a model of the UWSS. The reversed signals focus their energy on scatter sources (e.g., leaks, blockages, etc. in the pipes) in the UWSS with a resolution that improves with frequency and is proven to achieve the limit set by wave physics. Analogous to medical ultrasounds, imaging refers to the use of the intensity of TR to focus, identify, localize and characterize notable features, including defects. RGC's Monitoring and Assessment panel rated the progress as *"exemplary"* and the achievements as "*exceptional*".

The research has led to the establishment of a new and novel laboratory as well as field-proven techniques to diagnose pipe systems in real time. One US-based patent has been granted and two more are under preparation. We developed unique test beds in Hong Kong and Italy, where leaks, air blockages and unknown devices have been successfully identified. A live pilot facility installed for HKUST's water system has been developed. The success of this TRS project could not have been achieved without (i) the full support and engagement from the Water Supplies Department (WSD) in Hong Kong and the AcegasApsAmga SpA in Italy and (ii) the strong collaboration amongst outstanding researchers from HK, China, USA, Canada, NZ and Italy. The findings enable timely detection of UWSS defects and formulation of proactive mitigation measures and will crucially contribute to the sustainable development of HK through water conservation. RGC's Monitoring and Assessment panel commented: "*This is a large, coherent, and top-notch team carrying out work at the highest level on an important urban problem.*"