NSERC Alliance Project “Next-generation Wood Construction”

HQP Seminar-10

Energy Audit of Exterior Building Envelopes Using Infrared Thermography

Presenter

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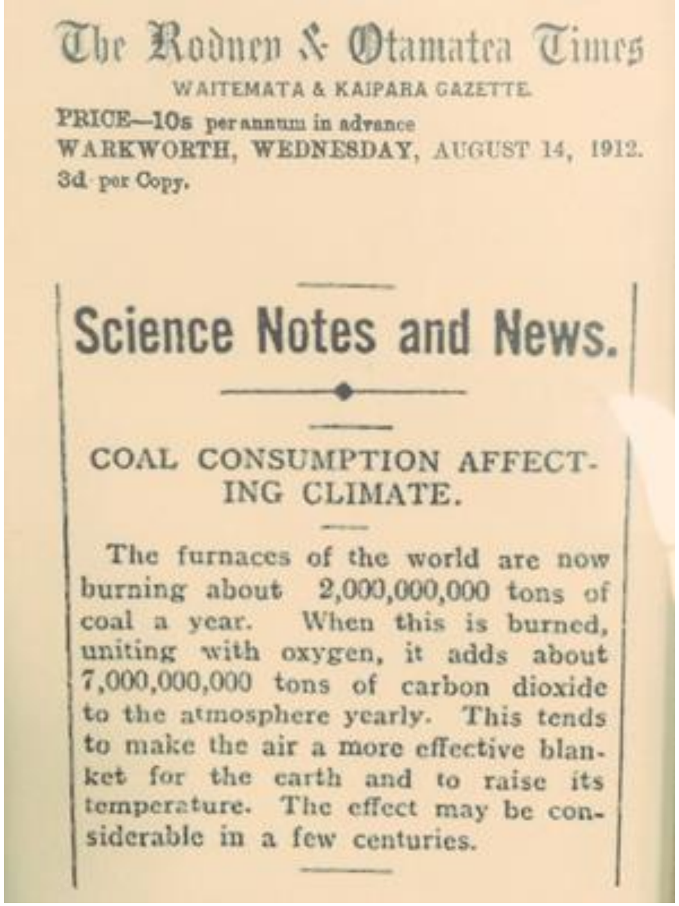
University of Victoria

Wednesday, June 26th, 2024

Climate Change Emergency



The Rodney & Otamatea Times

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Science Notes and News.

COAL CONSUMPTION AFFECTING CLIMATE.

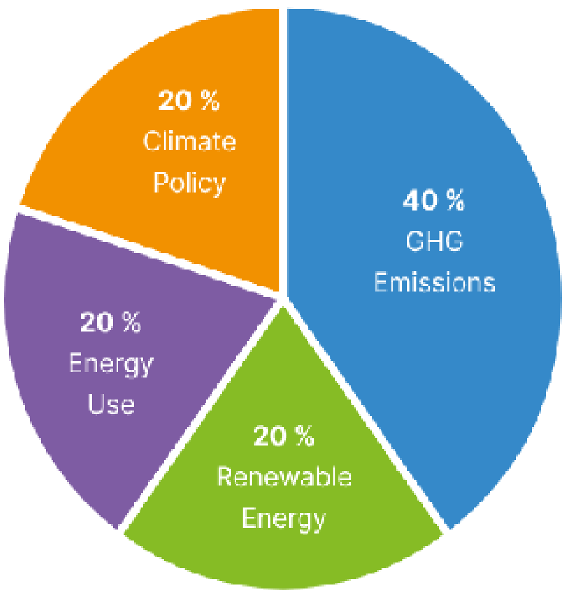
The furnaces of the world are now burning about 2,000,000,000 tons of coal a year. When this is burned, uniting with oxygen, it adds about 7,000,000,000 tons of carbon dioxide to the atmosphere yearly. This tends to make the air a more effective blanket for the earth and to raise its temperature. The effect may be considerable in a few centuries.

"…… Some people can just let things go, but I can't, especially if there's something that worries me or makes me sad. ……." ***Greta Thunberg***

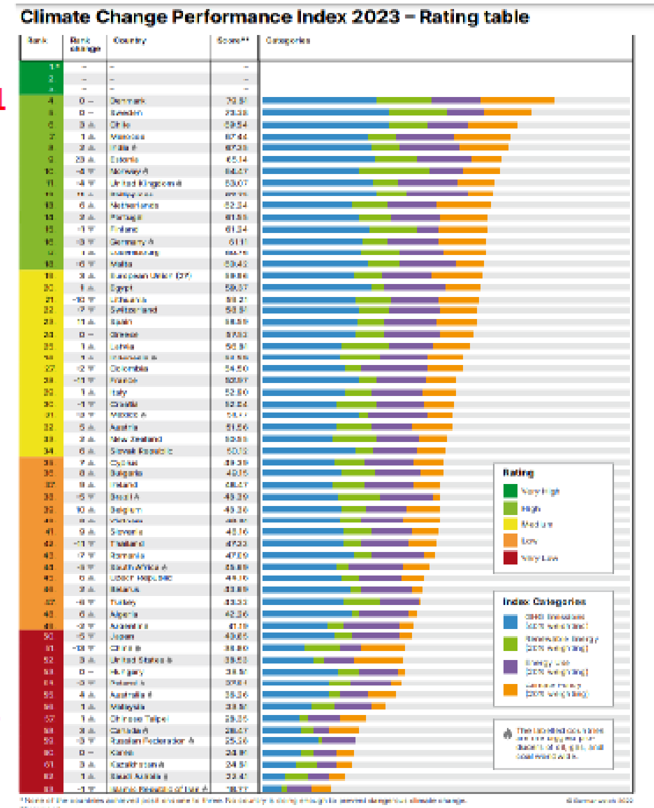
The Big Picture: Why Green?

Climate Change Performance Index 2023

The CCPI evaluates 63 countries and the European Union, which together generate 90%+ of global greenhouse gas emissions.



4. Denmark – 79.61



58. Canada – 26.47

Outline

- Background
- Development of Quantitative IRT Methodologies
- Challenges/Opportunities in IRT with UAVs
- Development of IRT Webtool
- Conclusions

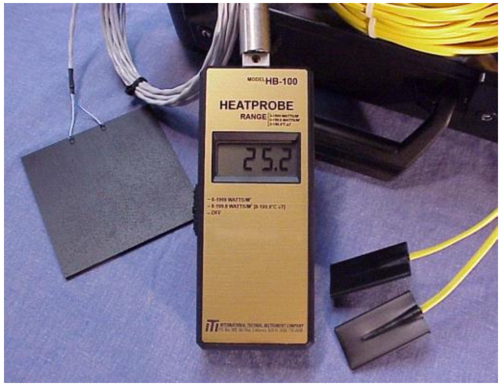
Background

Current practices:

- Nominal Design U-value (reference tables in building codes)
- Age/Condition assessment of envelope
- Building size (Floor area, Volume, etc.)
- Energy use intensity (EUI)
- In-situ measurement heat flux meter (HFM)
- Qualitative infrared thermography (IRT)

Background

- Point measurement
- Long measuring time (at least 72 hours)
- Affected by environmental conditions
- Neglect the effect of thermal bridges and the moisture content of materials
- Invasive (mainly installed on the interior surface)



Background

- Non-destructive
- Internal and External thermography (Non-invasive)
- Consider the real condition of buildings (degradation of materials)
- Determining non-homogenous areas (damage/ voids)
- Sources of air leakage
- Moisture
- Thermal bridges
- Location of missing insulation

Why In-Situ Assessment of building envelopes?

The current methods of quantitative energy audits of buildings:

- May not represent the actual/real thermal performance of the building envelope
- Are time-consuming & expensive (e.g., HFM & 3D simulation tools)

Instead, we need a quantitative approach which is:

- Non-Destructive
- Comprehensive
- Rapid
- Real-time

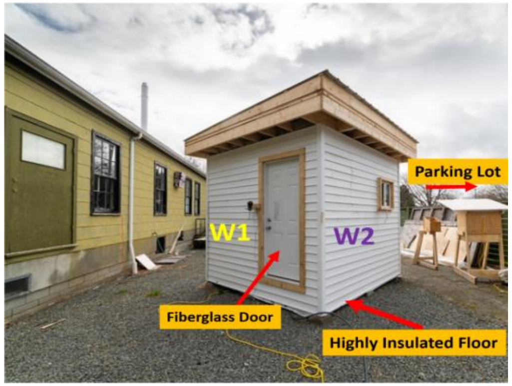
Non-Destructive Technology: Infrared Camera

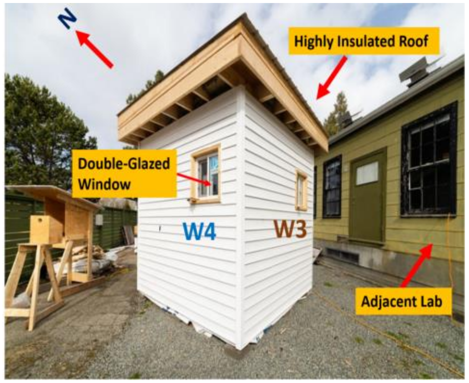
- Non-invasive
- Real-time Diagnosis
- Non-homogenous detection
- Sources of air leakage
- Moisture
- Thermal bridges
- Location of missing insulation
- **Quantify Heat losses?**

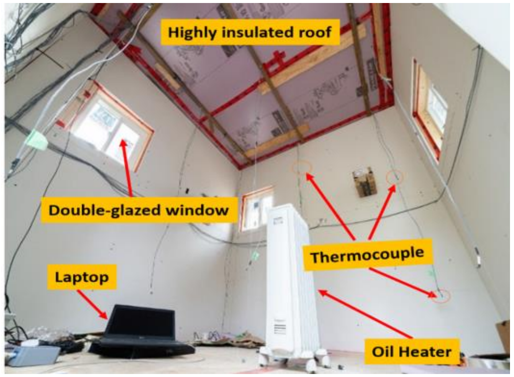
Objectives

- ❑ Develop **in-situ quantitative approaches** for heat loss estimation of wall assemblies.
- ❑ Develop a **relative quantitative metric** for rapid evaluation and subsequent ranking of building envelope thermal performance.
- ❑ Evaluate the potential of **IRT with Unmanned Aerial Vehicles (UAV)** for quantitative thermal assessment of building envelopes
- ❑ Develop a **web-based tool** for thermal assessment of building envelope and opportunities for improvement.

Research Experimental Set-up







Wood-Framed Structure (Exterior) **Wood-Framed Structure (Interior)**

Wall Assemblies	1D R-value
W1 (Interior insulated 2×4)	R-14
W2 (Interior insulated 2×6)	R-22
W3 (Interior and exterior insulated wall with metal furring and z-girts, 2×6)	R-22 + R-10
W4 (Interior and exterior insulated with wood-strapping, 2×6)	R-22 + R-10

Equipment: IR camera, Temperature Sensors, Heater, Energy Meter, Anemometer

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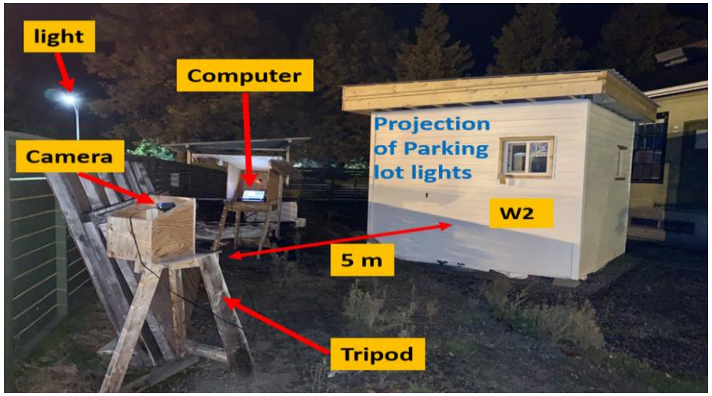
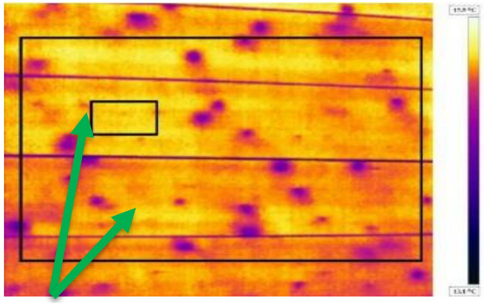
Procedure & Data Acquisition

Environmental conditions

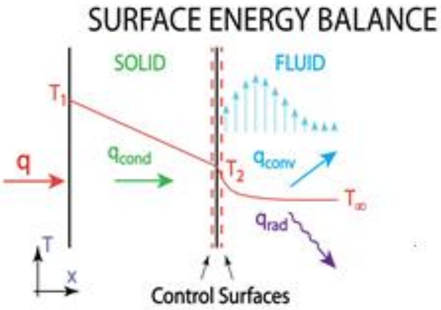
- Temperature gradients (10-15 K)
- Time of test (late evening)
- Rain/Snow (24 hours prior to test)
- Wind speed (< 1 m/s)
- Sky condition (cloudy)



U-value estimation with external IRT



Region of Interest (ROI)



Heat balance on the surface

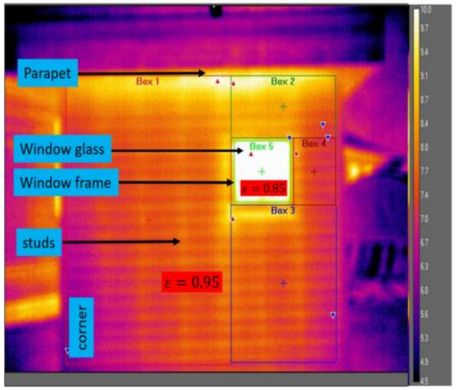
$$U_{overall} = \frac{Radiation + Convection}{T_{in} - T_{out}}$$

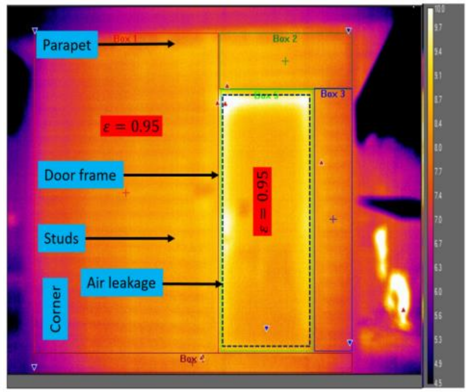
$$U_{overall} = \frac{\varepsilon\sigma(T_s{}^4 - T_{out}{}^4) + h_c(T_s - T_{out})}{T_{in} - T_{out}}$$

Measured by IR camera

T_{in} is the indoor air temperature (C), T_{out} is the outdoor air temperature (C), ε is emissivity of wall, σ Stefan-Boltzmann constant, and h_c is the convective heat transfer coefficient (W/m^2 K).

Opaque Wall Effective U-value Estimation





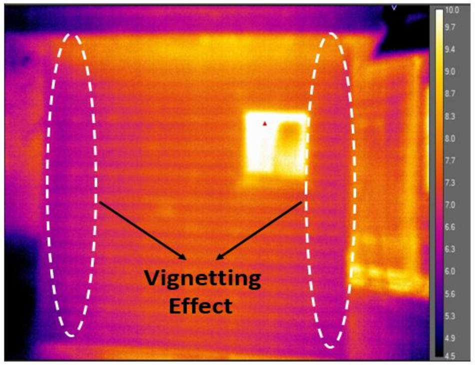
$$T_{s,avg} = \frac{T_1 * A_1 + T_2 * A_2 + T_3 * A_3 + \cdots + T_i * A_i}{A_T}$$

$$U_{overall} = \frac{\varepsilon\sigma\left(T_{s,avg}{}^4 - T_{out}{}^4\right) + h_c\left(T_{s,avg} - T_{out}\right)}{T_{in} - T_{out}}$$

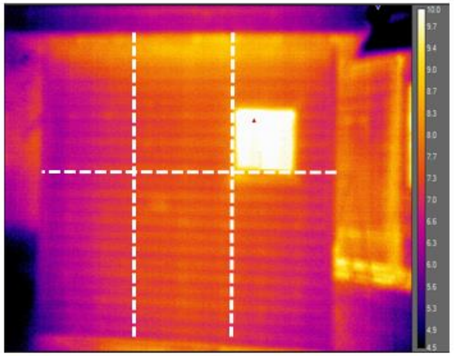
Wall assemblies	IRT-estimated U-value (W/m² K)	3D simulated U-value (W/m² K)	Deviations (%)
Day1			
W1	0.37	0.43	-13.95
W2	0.22	0.31	-29.03
W3	0.09	0.26	-65.38
W4	0.04	0.24	-83.33
Day 2			
W1	0.35	0.43	-18.60
W2	0.26	0.31	-16.13
W3	0.11	0.26	-57.69
W4	0.06	0.24	-75.00
Day 3			
W1	0.37	0.43	-13.95
W2	0.25	0.31	-19.35
W3	0.15	0.26	-42.31
W4	0.10	0.24	-58.33

- ✓ U-values were not identical on different days.
- ✓ Deviations were more for well-insulated wall (W3 and W4)
- ✓ Adverse effect of vignetting (colder corners) on accuracy of results.

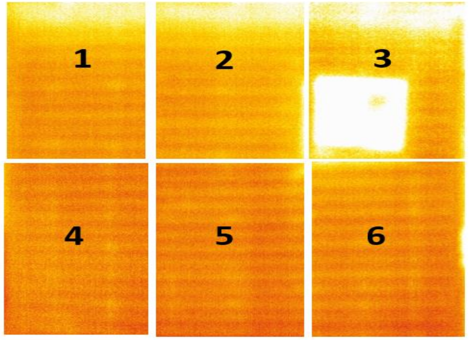
Novel IRT U-value Estimation Enhancement



Vignetting Effect



Dividing to 6-segments



6 IRT shots from different angles

Wall assemblies	IRT-estimated U-value (W/m² K)	3D simulated U-value (W/m² K)	Deviation (%)
W1	0.42	0.43	-2.33
W2	0.29	0.31	-6.45
W3	0.23	0.26	-11.53
W4	0.21	0.24	-12.50

Comparative assessment of energy models and metered energy data

Magnitude of error in simulated energy models and actual data.

Calibration criteria	Deviations of Models			
	1D- IRT	IRT-with vignetting	IRT-with vingetting correction	ASHRAE Guideline 14
NMBE (%)	22.04%	21.60%	3.59%	±5%
CVRMSE (%)	39.30%	38.52%	8.93%	15%

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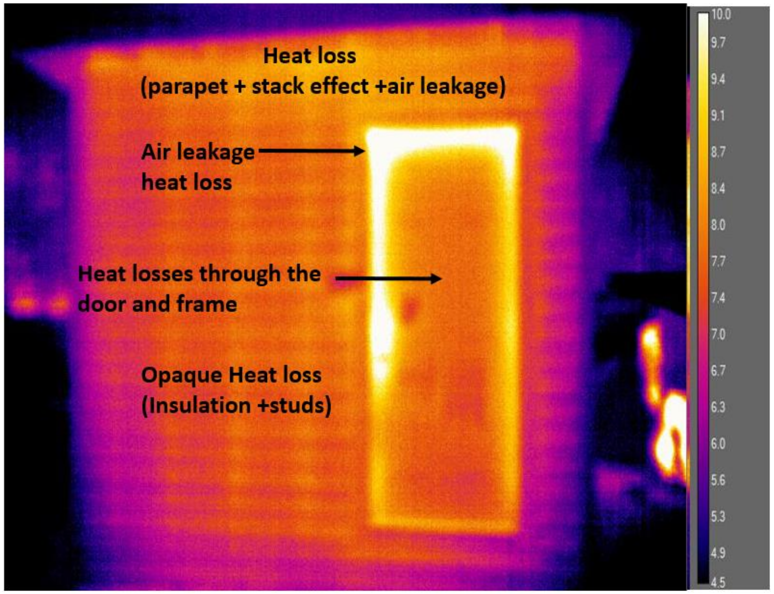
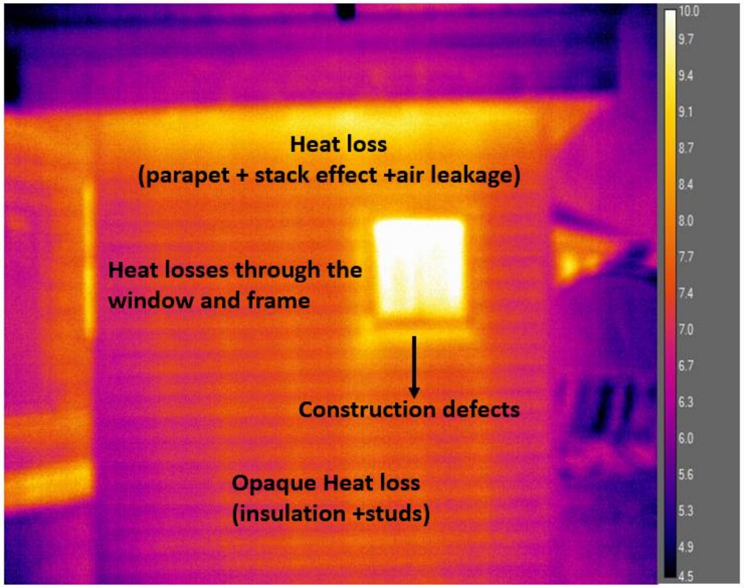
Large-Scale Ranking Metric Using IR Camera

Infrared Index

We need a metric which:

- Considers the overall performance of building envelop(all sources of losses)
- Provides an opportunity for rapid in-situ ranking of the building envelope.





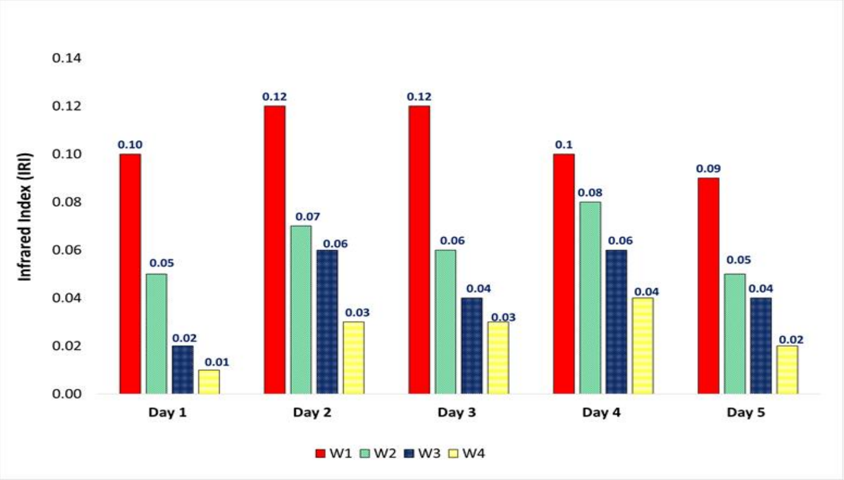
$T_{s,avg}$ is the average surface temperature (C)
T_{in} is the indoor air temperature (C)
T_{out} is the outdoor air temperature (C)

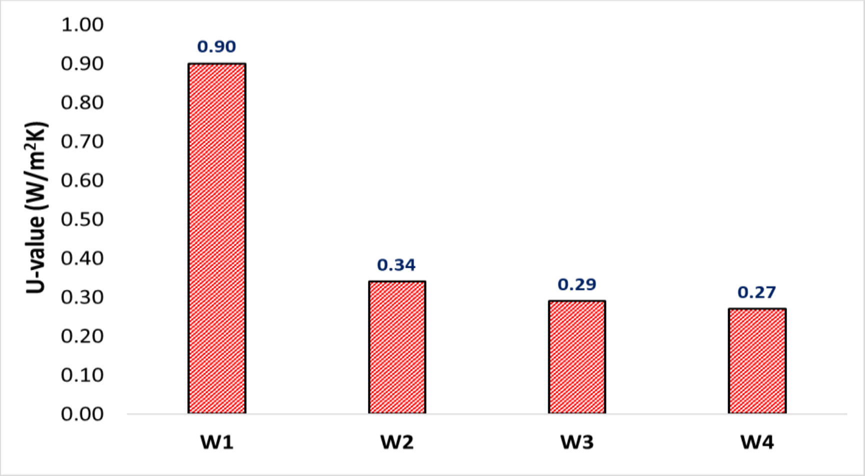
$$Infrared\ Index\ (IRI) = \frac{T_{s,avg} - T_{out}}{T_{in} - T_{out}}$$

Steady-State Condition

Large-Scale Ranking Metric Using IR Camera

Infrared Index

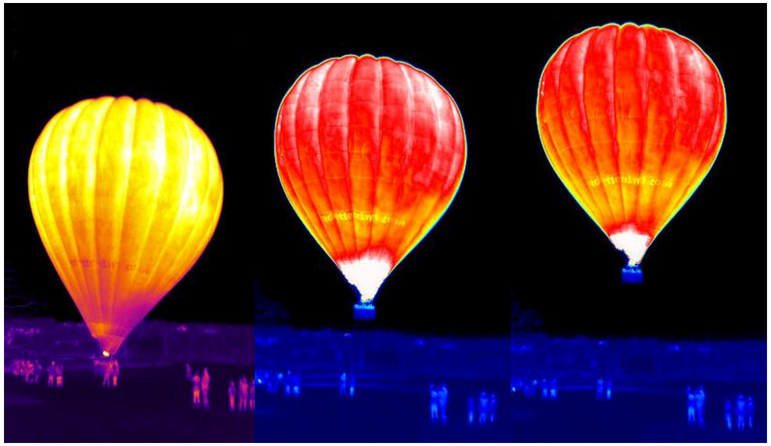




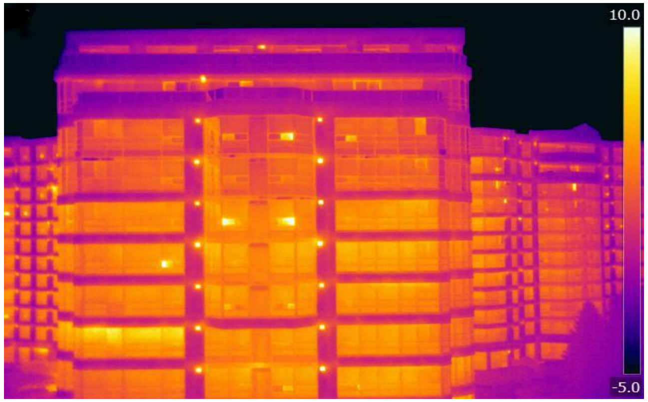
- ✓ IRI showed a similar ranking in different external conditions.
- ✓ IRI ranking was similar to the overall U-value (opaque wall + fenestration) ranking.
- ✓ More thermal anomalies in the building envelope can lead to a higher IRI and a poorer overall thermal performance.
- ✓ Higher levels of insulation do not necessarily ensure better building energy performance if air leakage, construction defects, and thermal bridging effects are substantial.

Dynamic Quantitative Energy Assessment Using IR Camera

IRT- Airship



IRT- hot-air ballons



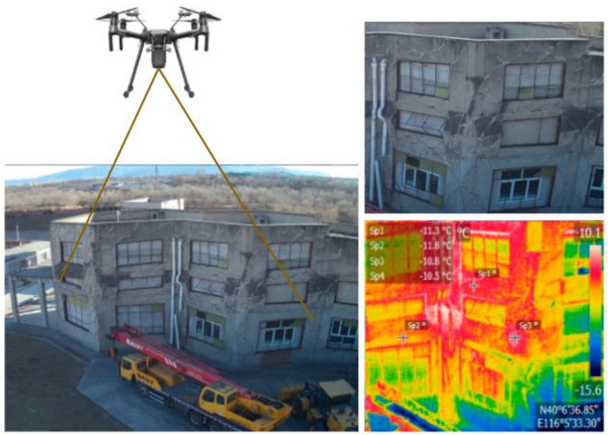
IRT- Crane

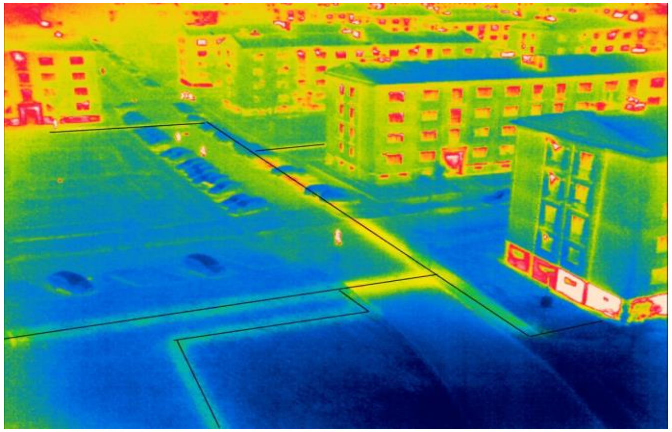
Challenges:

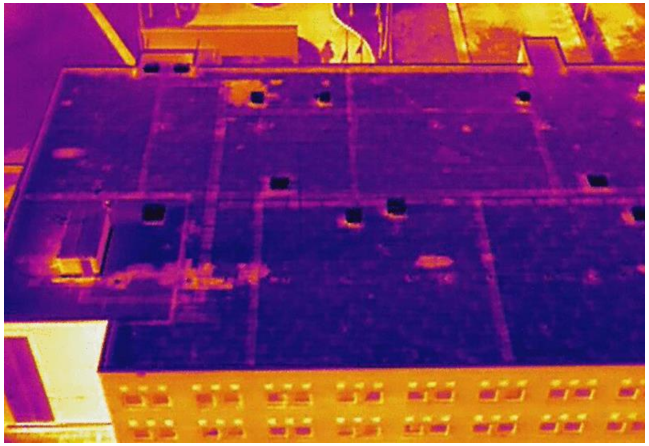
- Safety
- Complexities of manual flight operations
- Vibrations
- Distance and limited resolution of sensors
- Quality of the captured thermal infrared images (blurriness)

Dynamic Quantitative Energy Assessment Using IR Camera

IRT using Unmanned Aerial Vehicles (UAVs)





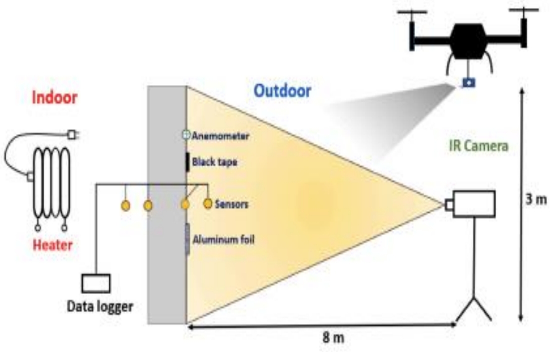


Advantages:

- Rapid (Opportunities for periodic monitoring)
- Enhances the resolution and temperature measurement accuracy
- Real-Time Data Collection
- Safety & Cost-Effectiveness

Dynamic Quantitative Energy Assessment Using IR Camera

UAV-IR camera



Schematic Design

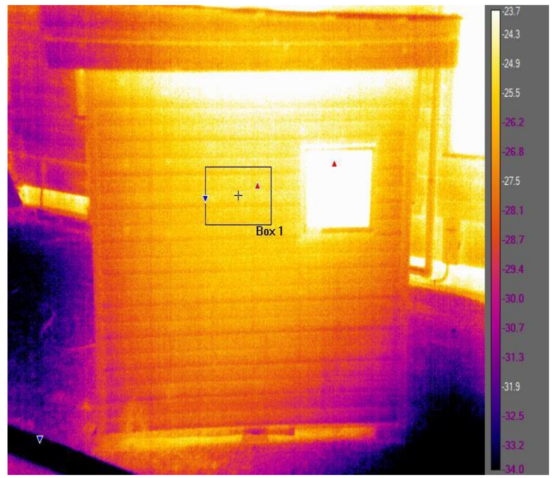
Field Measurement

- Compare the accuracy of dynamic measurements with stationary IRT.
- Delineate the differences between functionality of IR camera in dynamic and static measurements
- Determine the challenges and opportunities to enhance the accuracy of results.

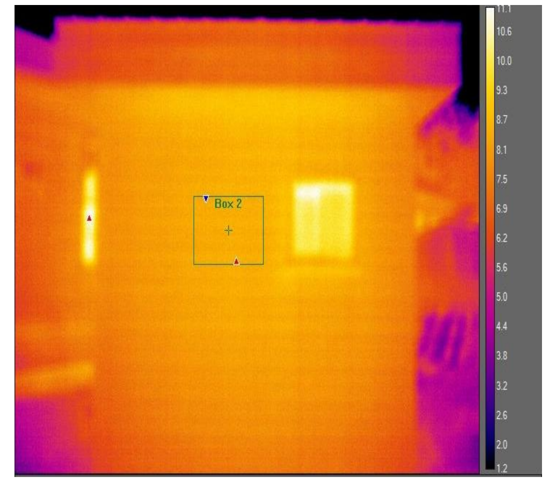
Dynamic Quantitative Energy Assessment Using IR Camera

Dynamic vs. Static measurements

Visual Image



Dynamic (UAV) T= 2ºC



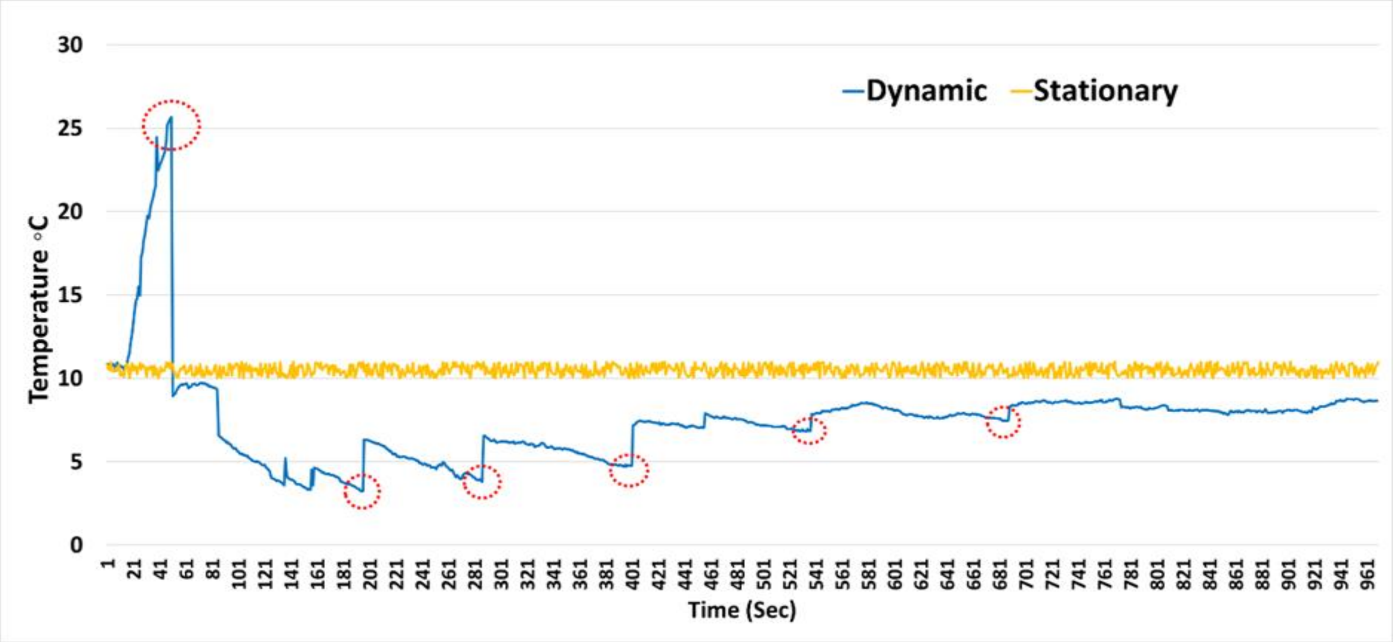
Static (Handheld Camera) T= + 11.2 ºC

Initial Observations

- Dynamic IRT measurements may not as accurate as stationary measurements.
- Environmental conditions (e.g., wind) may influence the accuracy of dynamic IRT unlike controlled conditions like laboratory.
  - Thermal cameras demonstrated similar measurements in the lab conditions (comparable).

Dynamic Quantitative Energy Assessment Using IR Camera

Time-series dynamic measurement



- A dramatic increase in temperature measurement shortly after take-off.
- Thermal sensor is affected by drone-induced wind during the flight.
- Sensors stabilize with environmental conditions during the flight.
- The temperature deviation after **16 minutes** was about **2 ºC**.

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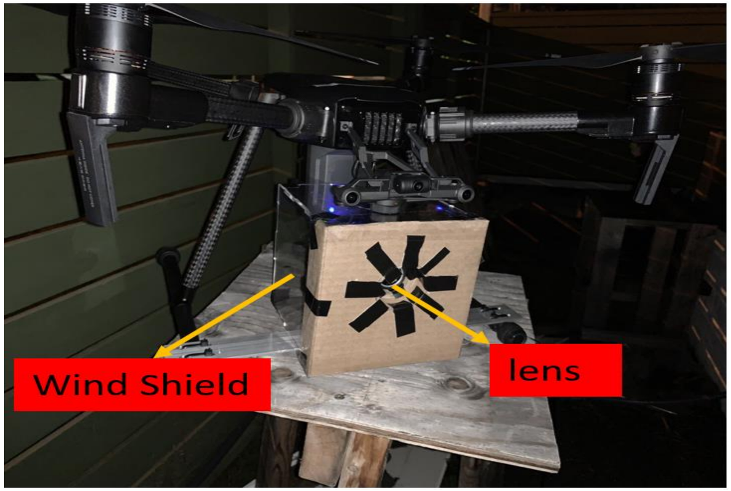
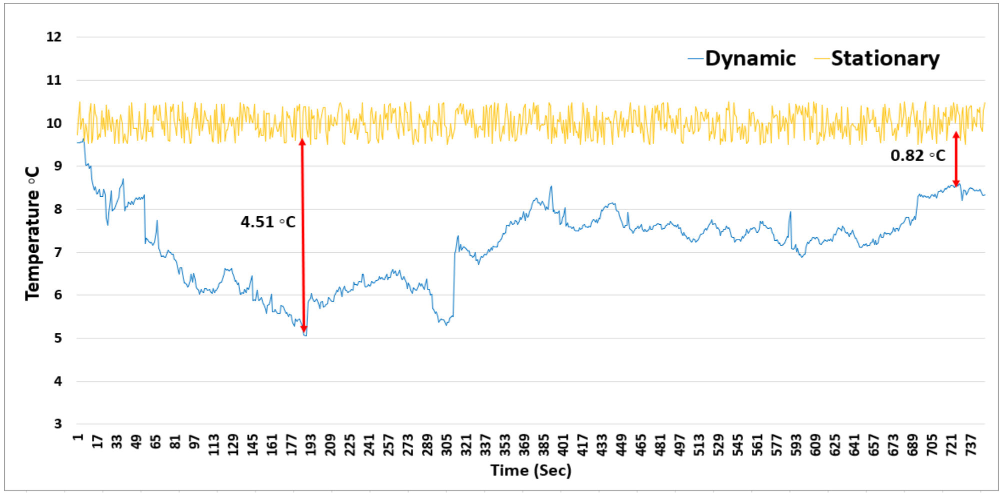
Dynamic Quantitative Energy Assessment Using IR Camera

Results- Effect of wind shield/stabilization





- Shield minimizes the effect of sudden turbulence around the camera during the flight **(Temperature drops less and stabilization faster).**
- Due to the duration of aerial surveys being **limited by battery life**, a shield facilitates faster camera stabilization consequently allowing for more data collection per flight.
- The proposed method could help decrease the deviation between dynamic and stationary measurements to less than 1 ºC (~ 12 minutes).

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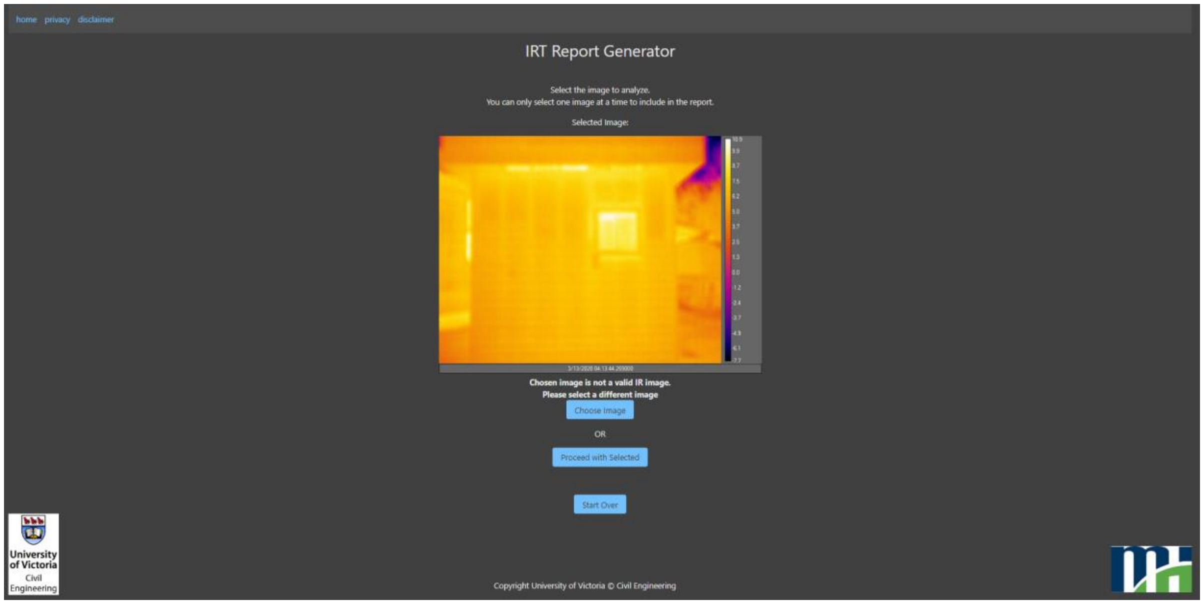
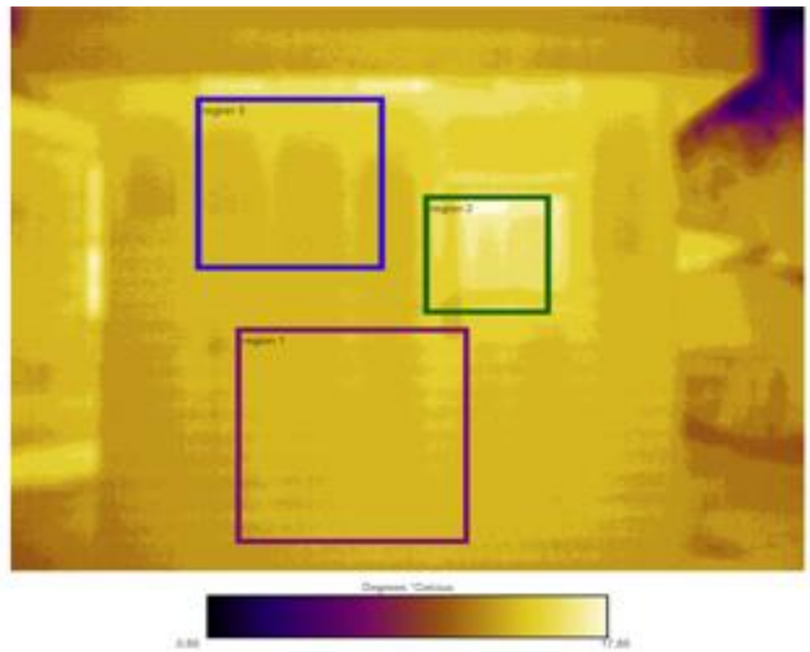
Quantitative IRT- Webtool Development



https://irt.cive.uvic.ca/

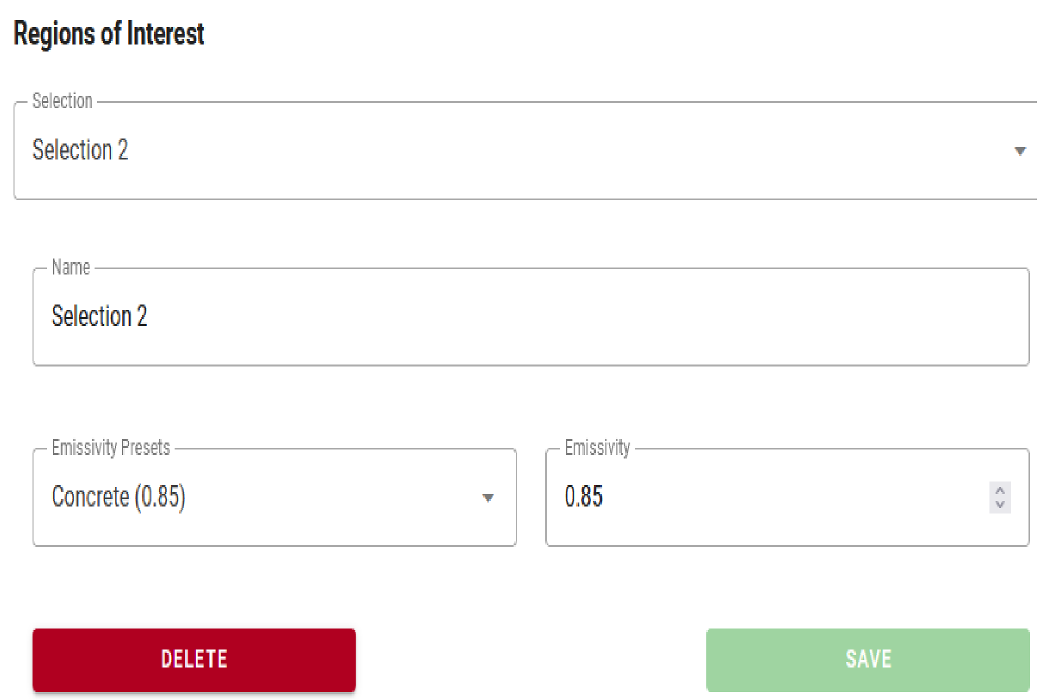
Quantitative IRT- Webtool Development

1- Selection of region of interest



Quantitative IRT- Webtool Development

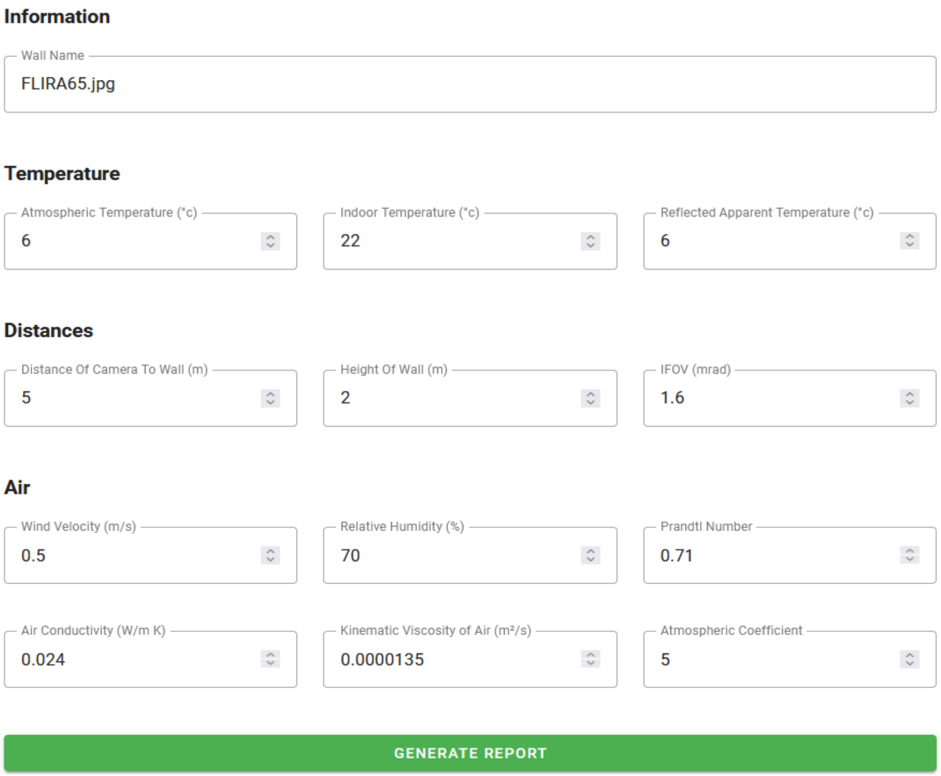
2- Select the material and emissivity



Quantitative IRT- Webtool Development

3- Boundary conditions Inputs

- Indoor and outdoor temperatures
- Camera Specs
- Outside environmental inputs for convection heat transfer coefficient calculations



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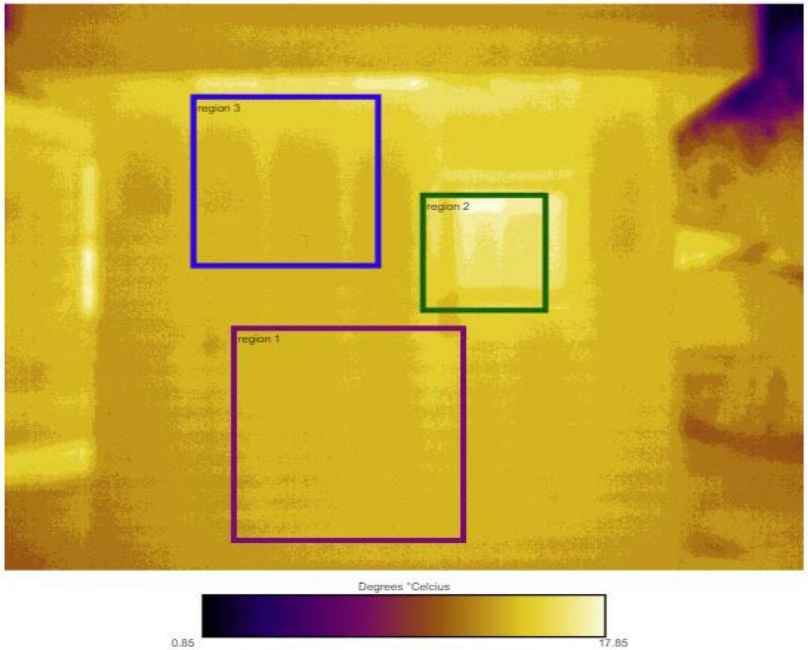
Quantitative IRT- Webtool Development

4- Report

- Area of ROIs
- Max/Min/Avg temperatures
- IRI values
- U-values

Analysis 1



Region (ROI)	Area (m²)	Mean Temp °C	Max Temp °C	Min Temp °C	IR Index (IRI)	U-value (W/m² K)
Region 1	1.33	11.2	15.85	0.85	12.78	0.26
Region 2	0.38	12.51	14.85	2.85	12.84	0.24
Region 3	0.85	14.44	17.85	12.85	12.93	0.25
Full Image		13.49	17.85	0.85	0.04	0.27

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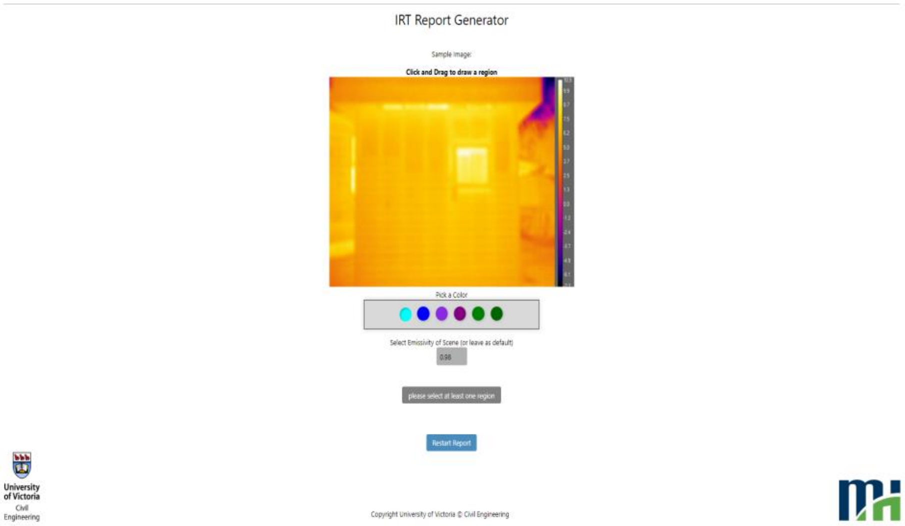
Quantitative IRT- Webtool Development



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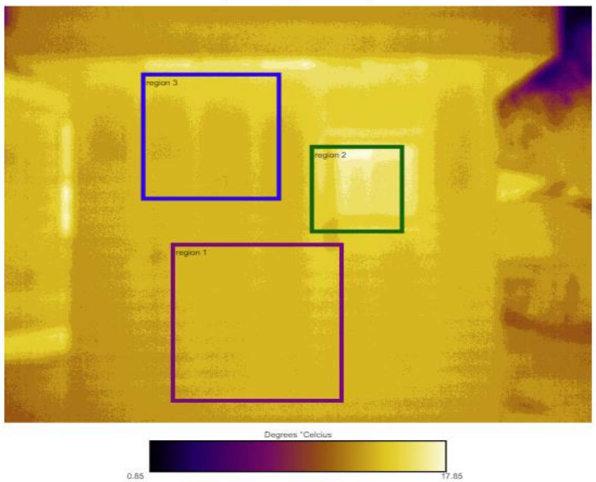
Analysis 1



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Region 3	0.85	14.44	17.85	12.85	12.93	0.25
Full Image		13.49	17.85	0.85	0.04	0.27

- User-Friendly (Citizens, Building Manager, Practitioner, Researcher)
- Motivating communities to retrofit their homes.
- Compatible with IR cameras (including the one for phones)
- Learning Opportunity for Students.

Conclusions

- Infrared thermography could be a reliable tool for rapid quantitative thermal assessment of building envelope (U-value & IR index).
- Quantitative IRT provides an opportunity for using the estimated U-value as an input for accurate calibration of building energy models for the existing buildings.
- While for the relatively new and carefully constructed structures, the thermal anomalies are expected to be minor; for older buildings or poorly detailed building envelope assemblies, the IR Index may be a more holistic representation of relative thermal performance than 3D-simulated U-values.
- IR Index provides the opportunity for quick surveys of a large number of buildings.

Conclusions

- Development of this kind of external IRT technique facilitates future utilization of UAVs equipped with infrared cameras for conducting large-scale quantitative surveys in a fraction of the time without the need for current intrusive methods.
- Study on IRT with UAVs provided opportunities to define a more robust thermal imaging protocol for the quantification of building envelope thermal performance.
- IRT Webtool provides complementary information for energy advisors, property managers and citizens to make informed decisions about building envelope thermal performance and opportunities for improvement.

Research Outcomes

- Mahmoodzadeh, M., Gretka, V., & Mukhopadhyaya, P. (2023). Challenges and Opportunities in Quantitative Aerial Thermography of Building Envelopes. ***Journal of Building Engineering***, 106214

- M. Mahmoodzadeh, V. Gretka, I. Lee, P. Mukhopadhyaya, Utilizing External Infrared Thermography to Assess Thermal Performance of Wood-Framed Building Envelopes in Canada, ***Journal of Energy and Buildings***. (2021) 111807

- M. Mahmoodzadeh, V. Gretka, K. Hay, C. Steele, P. Mukhopadhyaya, Determining overall heat transfer coefficient (U-Value) of wood-framed wall assemblies in Canada using external infrared thermography, ***Journal of Building and Environment***. 199 (2021): 107897.

- M. Mahmoodzadeh, V. Gretka, S. Wong, T. Froese, P. Mukhopadhyaya, Evaluating Patterns of Building Envelope Air Leakage with Infrared Thermography, ***Energies***. (2020) 13 (14), 3545.

Acknowledgments

THANK YOU!