Drones in Construction

April 23, 2022

CPWR
THE CENTER FOR CONSTRUCTION
RESEARCH AND TRAINING

Moderator: **Patricia Quinn,** Director, Energy Employees Department & Small Studies Program, CPWR

Panel:

Nebulizer-retrofitted drone deployment at residential construction sites -

Rod Handy, MBA, PhD, CIH, Professor, Family & Preventive Medicine, University of Utah

Using unmanned aerial systems for automated fall hazard monitoring in high-rise construction -

Masoud Gheisari, PhD, Assistant Professor, M.E. Rinker, Sr. School of Construction Management, University of Florida

A practical model for measuring and mitigating safety hazards generated by using UASs in construction -

Yiye Xu, Civil & Construction Engineering, Oregon State University

Welcome!

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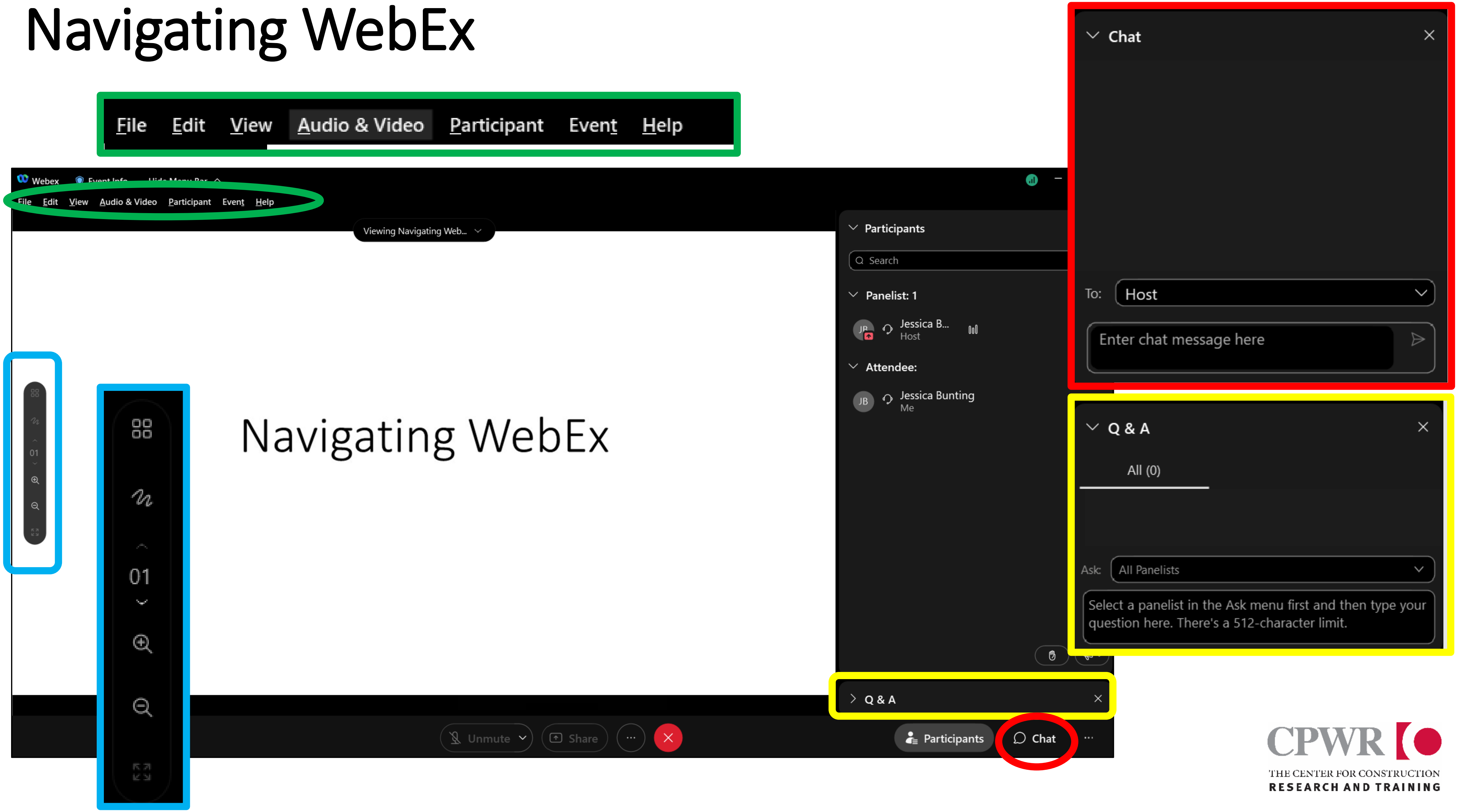
  Access code: **2554 177 7914** #

Navigating WebEx



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Nebulizer-Retrofitted Drone Deployment at Residential Construction Sites

PI – Rod Handy, MBA, PhD, CIH, University of Utah

Abbas Rashidi, PhD & Darrah Sleeth, PhD, MPH, CIH, University of Utah

Trenton Honda, PhD, MMS, PA-C, Northeastern University

Our Project Team…..

- Rod Handy, MBA, PhD, CIH (Principal Investigator)
- Trenton Honda, PhD, MMS, PA-C (Co-Investigator)
- Abbas Rashidi, PhD (Co-Investigator)
- Darrah Sleeth, PhD, MPH, CIH (Co-Investigator)
- Trent Henry, MS (Senior Research Associate)
- Ali Hassandokhtmashhadi (PhD student, Civil Engineering)
- Mohammad Farhadmanesh (PhD student, Civil Engineering)

Project Overview

- A water misting drone was deployed during the summer months of 2021 at two residential construction sites in Utah:
  - Salt Lake City
  - Saint George
- Area readings for Wet Bulb Globe Temperature (WBGT) and particulate matter (PM) concentrations were collected during 12 pilot test runs:
  - 10-minute pre-flight stage
  - 10-minute flight stage
  - 10-minute post-flight stage

Project Specific Aim #1

- *Develop and assess the effect of water-dispersing drones on air quality at residential construction sites. The hypothesis is that particulate matter (PM) concentrations, measured on residential construction sites immediately after water-dispersing drones are deployed during the excavation process, will be statistically significantly lower than the concentrations measured without the water-dispersing drones being deployed during similar residential construction excavation events.*

Project Specific Aim #2

- *Develop and assess the effect of water-dispersing drones on air temperature at residential construction sites. The hypothesis is that wet bulb globe temperatures (WBGT), measured on residential construction sites immediately after water-dispersing drones are deployed during the excavation process, will be statistically significantly lower than the WBGT measured without the water-dispersing drones being deployed during similar residential construction excavation events.*

Methods

- The main instrumentation/equipment used on this project included:
  - Two heat stress monitors
  - One particulate monitor
  - One DJI agricultural misting drone
  - Infrared distance measuring device
  - Tripod
  - Tall stepstool
- The misting drone was traversed at the 2 different sites:
  - Family Housing construction site on the University of Utah campus
  - St. George at The Ledges residential community

Methods (continued)

- Mean altitude of 20 feet
- The drone misted its 10 liter payload at 1 liter per minute for a duration of 10 minutes
- WBGT and PM data were collected at the center point of a 50’ x 50’ plot (250 ft^2) site
- The area WBGT was placed on a tripod at 3.5’ and the PM monitor was placed at approximately 5’ above ground level
- For each of the 12 test runs, data for both WBGT and PM was collected for 10 minutes to get a baseline (*pre*), during a 10 minute flight (*flight*), and for 10 minutes to get a post-flight condition (*post*)

Site Set-Up (St. George)

Site Set-Up (Salt Lake City)

Flight Traverse

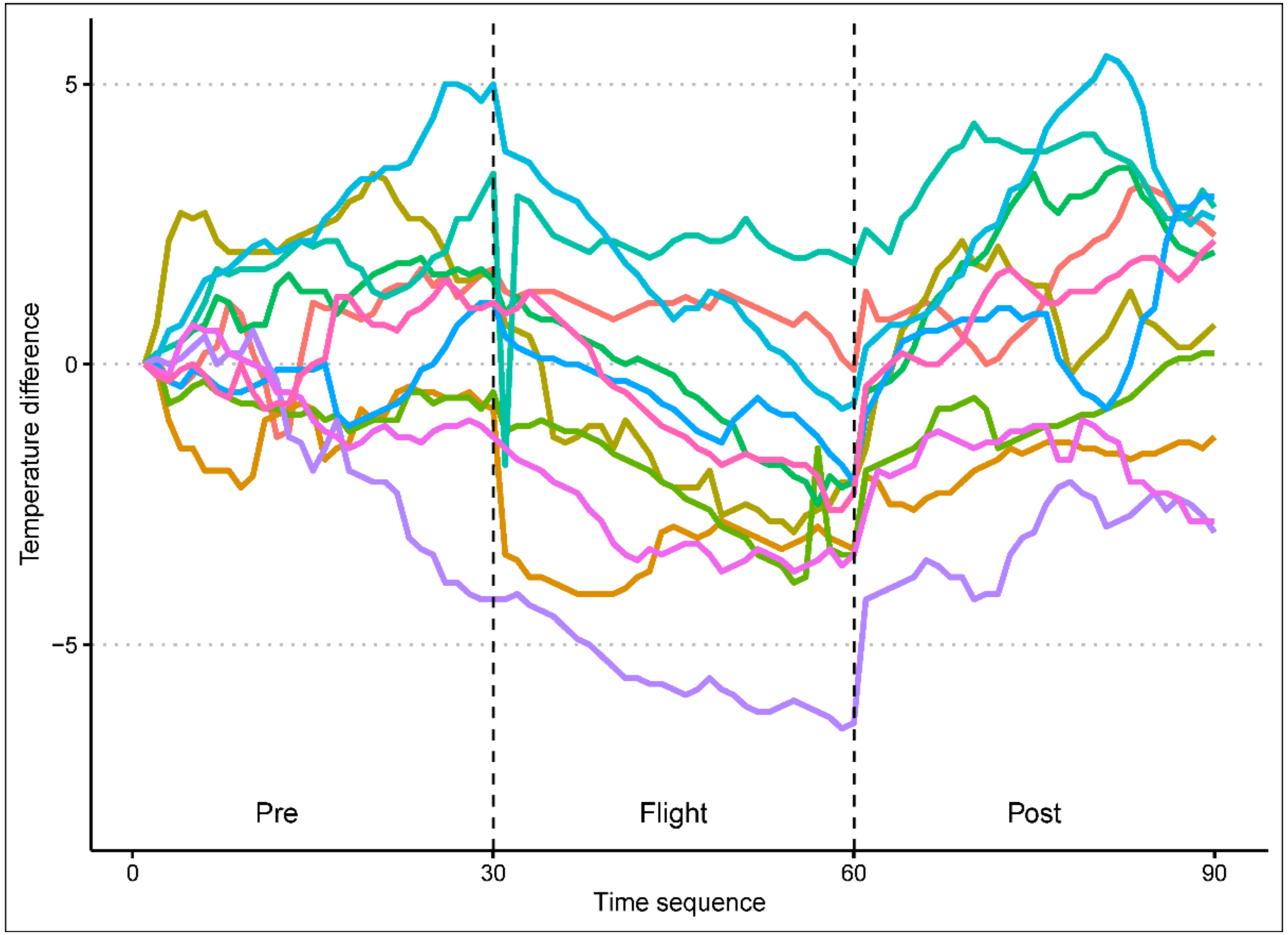
Key Findings

- During the drone flight stage of the test runs, the WBGT averaged 1.7 F degrees lower than both the pre-flight and post-flight stages of the test runs. This appears to support previous studies employing stationary nebulizers at construction sites.
- The drone flight stage was statistically significantly different ($p < 0.001$, $\alpha = 0.05$) than both the pre-flight and the post-flight stages.
- After the attempt at wet deposition of particulate matter during the drone flight stage of each of the test runs, the air was not statistically significantly cleaner than it was prior to the misting event.
- The battery life was a major constraint for all runs. This was due to the significant charge draining at a heavy water payload (i.e., 22 pounds or 10 liters initially).

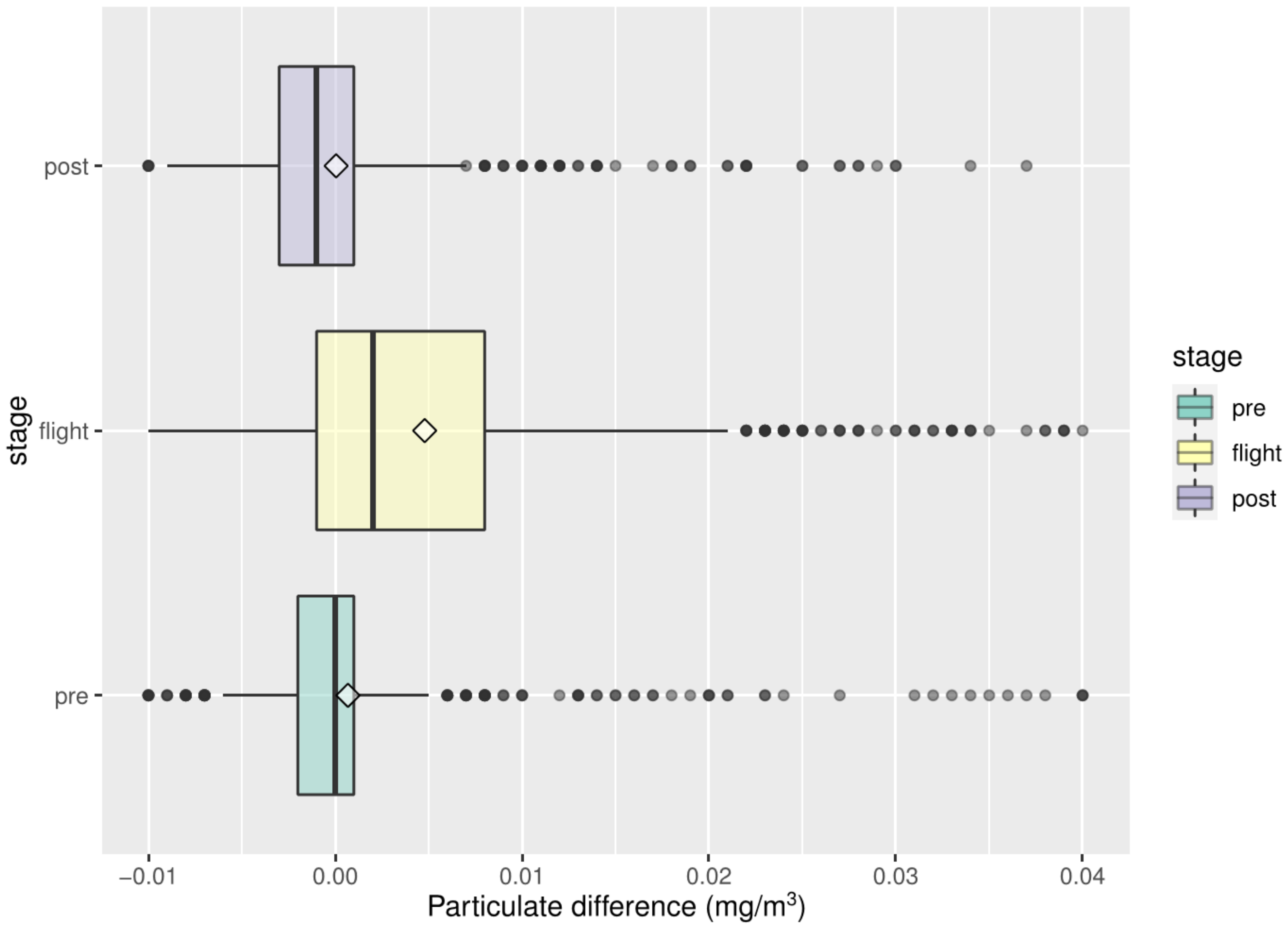
Key Findings (continued)

- While the average WBGT values from the test runs were 1.7 degrees F lower for the drone flight stages when compared to both pre-flight and post-flight sampling values, there were several times during the test runs where the WBGT values during flight were less than 3 degrees (i.e., > 3 degree reduction) that of both the pre-flight run values and post-flight run values.
- While the particulate matter concentrations were not statistically significantly different between the pre-flight ("dirty" air) and the post-flight ("clean" air), it was evident that at the beginning of the post-flight sampling that the particulate concentrations were normally marginally lower than at the end of the pre-flight test run. Hence, some minor particulate matter cleaning appeared to be resulting from the misting events.
- In order to get significant WBGT reductions and marginal air particulate cleaning at a particular residential constructions site, it will be necessary to keep drone(s) deployed almost continuously. With current battery technology, this will be challenging but still certainly plausible.

WBGT Results Profile



PM Results Profile



Recommendations and Conclusions

- From the results of this pilot study, it seems reasonable to pursue additional funding for a more comprehensive study involving heat stress and construction workers.
- This is further backed up by recent issues involving global climate change, outdoor workers, and chronic kidney disease.
- Thus, it is the intention of this research team to use the findings of this project to support a NIOSH-CDC R21 submission in the near term.
- At this time, it is not anticipated that PM characterization will be included as a part of this submission.

Masoud Gheisari, Ph.D.

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Drone, UAV, UAS, Flying Agent

Rotary Wing

- Most common in construction
- Vertical takeoff and landing
- Hovering capabilities
- Redundancy in propellers
- Better for rocky types of surfaces

Fixed Wing

- Longer flight endurance
- Resembles to traditional aircrafts
- Requires runways to takeoff/land
- Cannot hover
- Fly higher altitudes
- Carry heavier payloads
- Wider photogrammetric areas

Blimp

- Lighter-than-air vehicles
- Gain lift from indoor gas pressure
- Longest flying time

Flexible and Location-independent

Mounted With A Variety of Sensors

Time-efficient

Cost-efficient

Safe Deployment

Accurate and Precise

in Construction

Structural and Infrastructure Inspection	• Building Inspection • Bridge Inspection • Other Inspection (Roads, Photovoltaic Cells, Dams, Retaining Walls, Microwave Towers)
Transportation	• Landslide Monitoring and Mapping • Earthwork Volume Calculations • Traffic Surveillance
Cultural Heritage Conservation	• Historic Preservation and Reconstruction • Monitoring Historic Monuments • 3D Modelling of Heritage Buildings • Landscape Preservation
City/Urban Planning	• Land Policy Monitoring • Cadastral Surveying • City and Building Modeling • Cartography Updating
Progress Monitoring	• Construction Progress Monitoring • Tracking Material on Complex Jobsites
Post-Disaster Assessment	• Assessing Damages (Including Structural) of Cities/Buildings After Disastrous Events
Construction Safety	• Construction Safety Inspection • Monitoring Safety Hazards of Equipment in Construction Sites

in Construction

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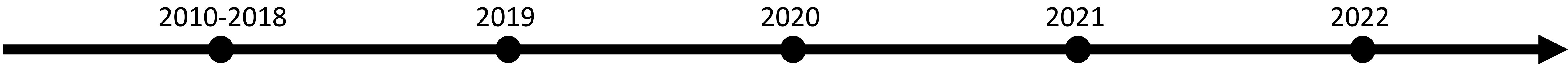


Drone4Safety

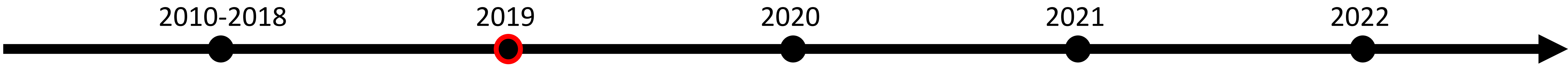
Safety4Drone

2010-2018 | 2019 | 2020 | 2021 | 2022

*Drone*4*Safety*

A User-centered Perspective

What do safety managers want from Drones?!

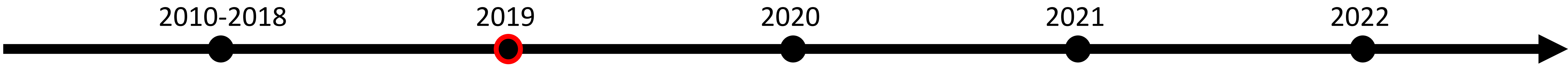


Drone4Safety
Application Areas

unsafe/inaccessible/hard-to-reach locations or blind spots

#	Hazardous Situation or Safety-Related Activity	Effectiveness		Frequency		Importance Factor
		Median	Average Rating	Median	Average Rating	
1	Using boom vehicles/cranes in the proximity of overhead power lines	5	4.30	4	3.80	16.31
2	Working in the proximity of boom vehicles/cranes	4	4.06	3	3.51	14.27
3	Working near unprotected edges/openings	5	4.02	3	3.44	13.85
4	Conducting post-accident investigations	4	3.77	4	3.64	13.69
5	Inspecting for the proper use of fall-protection systems	4	4.13	3	3.24	13.39
6	Inspecting house keeping	4	3.87	3	3.43	13.29
7	Working in the blind spots of heavy equipment	4	3.72	3	3.44	12.83
8	Inspecting at-risk rigging operations	4	3.77	3	3.36	12.67
9	Inspecting the requirements for ladders/scaffolds	3	3.47	2	3.00	10.40
10	Working in an unprotected trench	4	3.45	3	2.95	10.18
11	Working in the proximity of hazardous materials	3	3.30	3	3.00	9.91
12	Inspecting for the proper onsite use of PPE	3	3.32	3	2.95	9.81
13	Inspecting confined space entries	3	3.26	2.5	2.86	9.32
14	Using UASs to deliver safety messages to construction workers	3	2.92	2	2.56	7.47
15	Inspecting ergonomics conditions	2	2.54	1.5	2.39	6.07
16	Inspecting for the appropriate use of guarding machinery	2	2.55	2	2.23	5.69
17	Inspecting for the appropriate use of tag-out/lock-out procedures	2	2.49	1	2.16	5.37

***Gheisari, M.,** & Esmaeili, B. (2019). Applications and requirements of unmanned aerial systems (UASs) for construction safety. Safety Science, 118, 230-240.*



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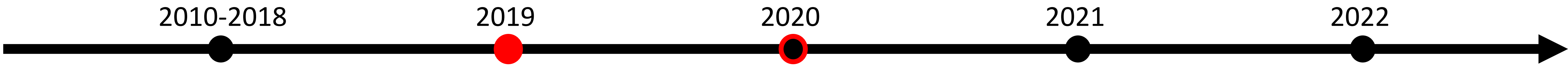
Challenges

#	Variable	Importance	
		Median	Average Rating
1	Liability and legal concerns	5	4.95
2	Safety concerns	5	4.93
3	Technical challenges	5	4.58
4	Requirement for a certified pilot/operator	5	4.53
5	Extensive training requirements	5	4.51
6	Confined or congested areas	5	4.47
7	Challenges associated with various weather conditions	5	4.33
8	Large capital investment	4	4.30
9	People are not aware of such technology	5	4.28
10	Application in limited types of projects	5	4.21
11	Lack of regulations regarding the safe distance of a UAV	4	4.14
12	Dynamic nature of construction projects	4	3.70
13	UAV limitations in communicating with the craft in real time	4	3.67
14	Challenges associated with using the technology at night	4	3.60
15	Time consumption	3	3.51

Gheisari, M., *& Esmaeili, B. (2019). Applications and requirements of unmanned aerial systems (UASs) for construction safety. Safety Science, 118, 230-240.*



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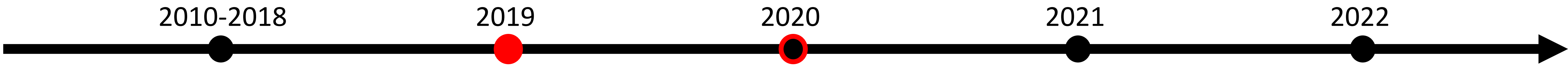
Drone Integration in Current Construction Safety Planning and Monitoring Processes



Drone4Safety

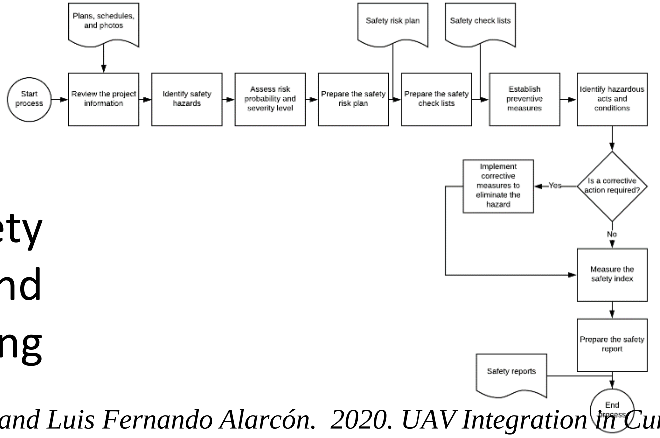
UAV Integration in Current Construction Safety Planning and Monitoring Processes

Actual Flights:

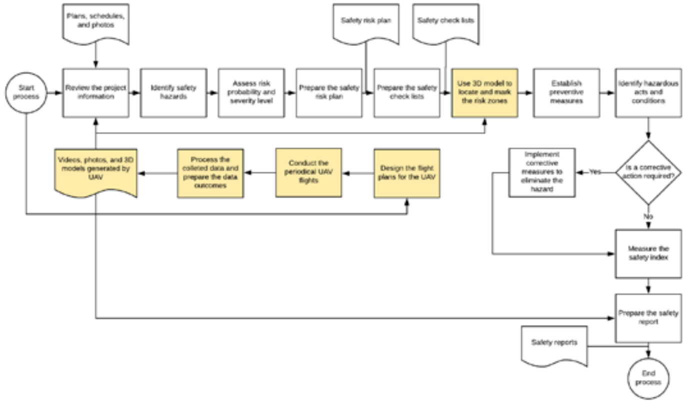
Four 23-story + Two 6-story buildings @ a land area of 16,850 m²

Point Cloud Data:

Regular Safety Planning and Monitoring



Drone-based Safety Planning and Monitoring



*Jhonattan G. Martinez, **Masoud Gheisari**, and Luis Fernando Alarcón. 2020. UAV Integration in Current Construction Safety Planning and Monitoring Processes- Case Study of a High-Rise Building Construction Project in Chile. ASCE Journal of Management in Engineering. 36/3: https://doi.org/10.1061/(ASCE)ME.1943-5479.0000761*

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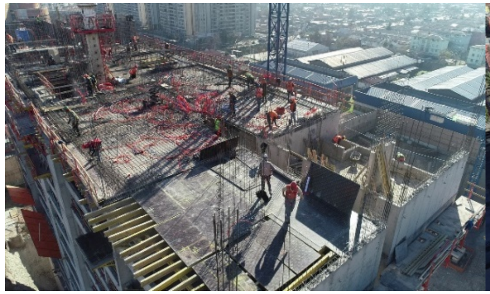
UAV Integration in Current Construction Safety Planning and Monitoring Processes

Regular Images

Worker distribution on the job site

A worker in a proximity to openings and edges



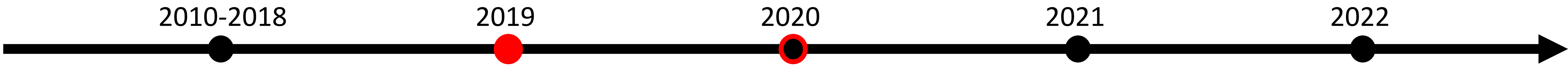
Lack of guardrails

Worker without safety rope

Point Cloud Data

	Issue # 1	Issue # 2	Issue # 3
Visual inconsistency identified			
Visual inconsistency type	Distortion	Lack of image overlap	Missing object
Visual inconsistency fixed			
Solution	Reduce the UAV speed to improve the image quality	Increase the number of model oblique images and the overlap percentage	Capture images when the object is not in movement

*Jhonattan G. Martinez, **Masoud Gheisari**, and Luis Fernando Alarcón. 2020. UAV Integration in Current Construction Safety Planning and Monitoring Processes- Case Study of a High-Rise Building Construction Project in Chile. ASCE Journal of Management in Engineering. 36/3: https://doi.org/10.1061/(ASCE)ME.1943-5479.0000761*



Drone4Safety

Drone Customizations

- *Enhancing PCD accuracy*
- *Automated hazard identification*
- *Making Drone flights safer*
  - *e.g., Drone recovery systems + Super Optical Zoom Capabilities*

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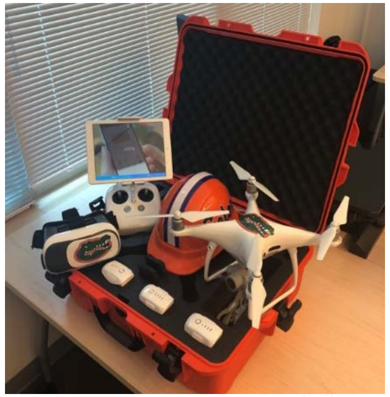
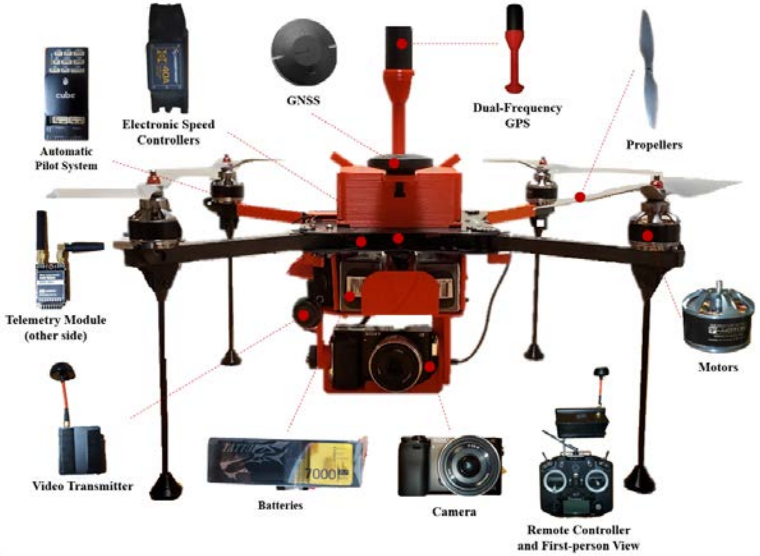
2010-2018 | 2019 | 2020 | 2021 | 2022

Drone4Safety
Enhancing Point Cloud Accuracy

Off-the-shelf UAVs: DJI Phantom Pro V.2



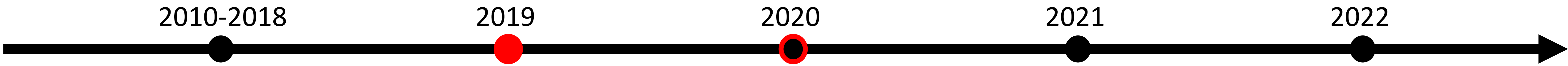
UAV with a dual-frequency GPS:



Ground control points:

UAV flight mission:

Jhonattan Martinez, Gilles Albeaino, ***Masoud Gheisari****, Walter Volkmann, and Luis F. Alarcón. 2020. UAS Point Cloud Accuracy Assessment Using SfM-based Photogrammetry and PPK Georeferencing Technique for Building Surveying Applications. ASCE Journal of Computing in Civil Engineering, Special Collection on Unmanned Aerial Systems (UASs) in AECO Industry https://doi.org/ 10.1061/(ASCE)CP.1943-5487.0000936*



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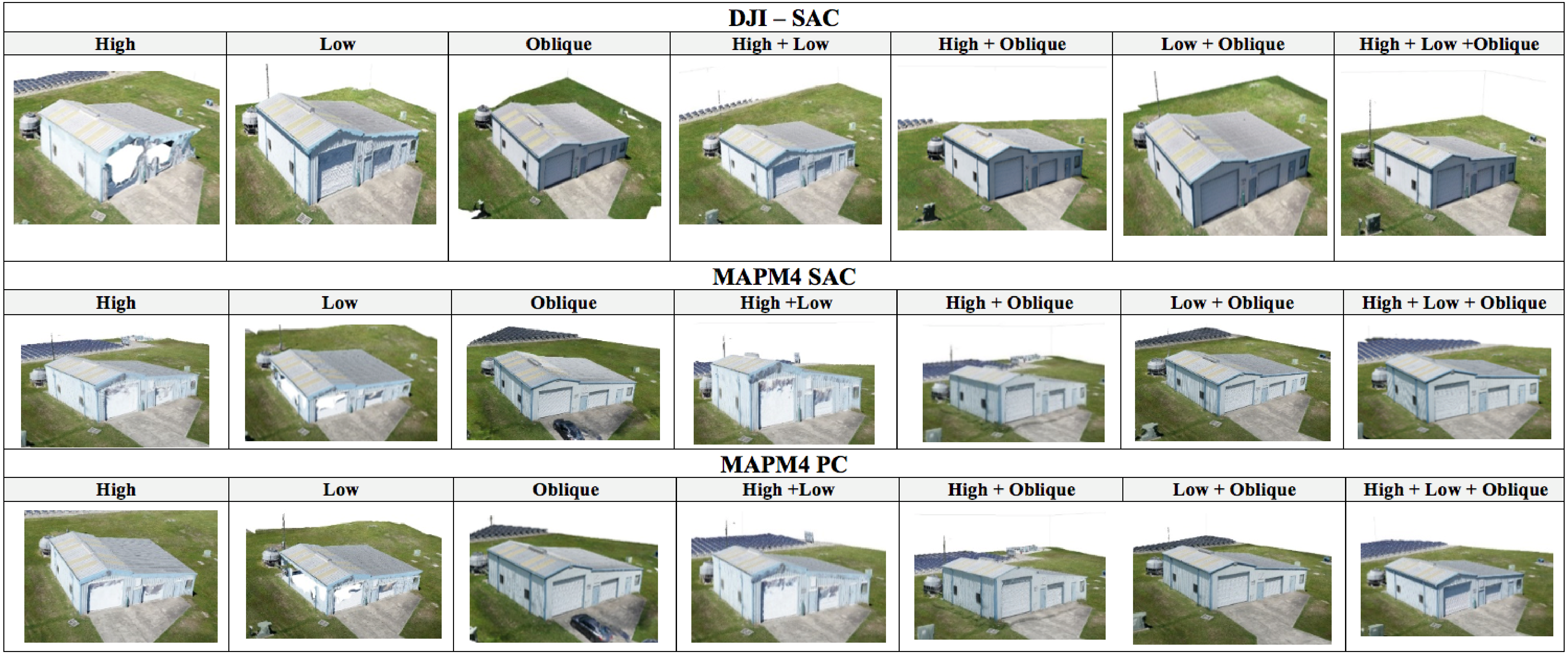
Enhancing Point Cloud Accuracy



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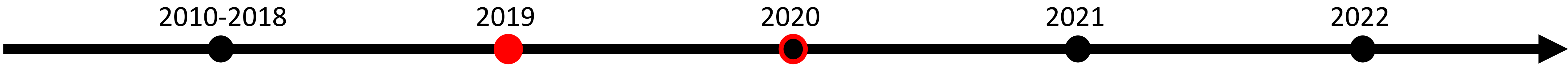

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Enhancing Point Cloud Accuracy

			Level of PCD Accuracy[1]					PCD Processing Time[2]
			Planimetric and Altimetric Error Analyses				Actual Field Measurements	
UAS Model	**GPS Type**	**PPK Correction?**	**MAE_X**	**MAE_Y**	**MAE_Z**	**ME**	**ME**	
P4P-SAC	L1	No	Average	Average	Very Low	Very Low	High	Medium
MP4-SAC	L1/L2	No	High	Average	Low	Low	High	Long
MP4-PC	L1/L2	Yes	Very High	Very High	Very High	Very High	Very High	Long

[1] *Level of PCD Accuracy: Very High: <0.100, High: 0.100–1.000, Average: 1.000–10.000, Low: 10.000–50.000, Very Low: > 50.000*

[2] *PCD Processing Time: Short: <1 Hour, 1 Hour <Medium<10 Hour, Long>10 Hours*

*Jhonattan Martinez, Gilles Albeaino, **Masoud Gheisari**, Walter Volkmann, and Luis F. Alarcón. 2020. UAS Point Cloud Accuracy Assessment Using SfM-based Photogrammetry and PPK Georeferencing Technique for Building Surveying Applications. ASCE Journal of Computing in Civil Engineering, Special Collection on Unmanned Aerial Systems (UASs) in AECO Industry https://doi.org/ 10.1061/(ASCE)CP.1943-5487.0000936*

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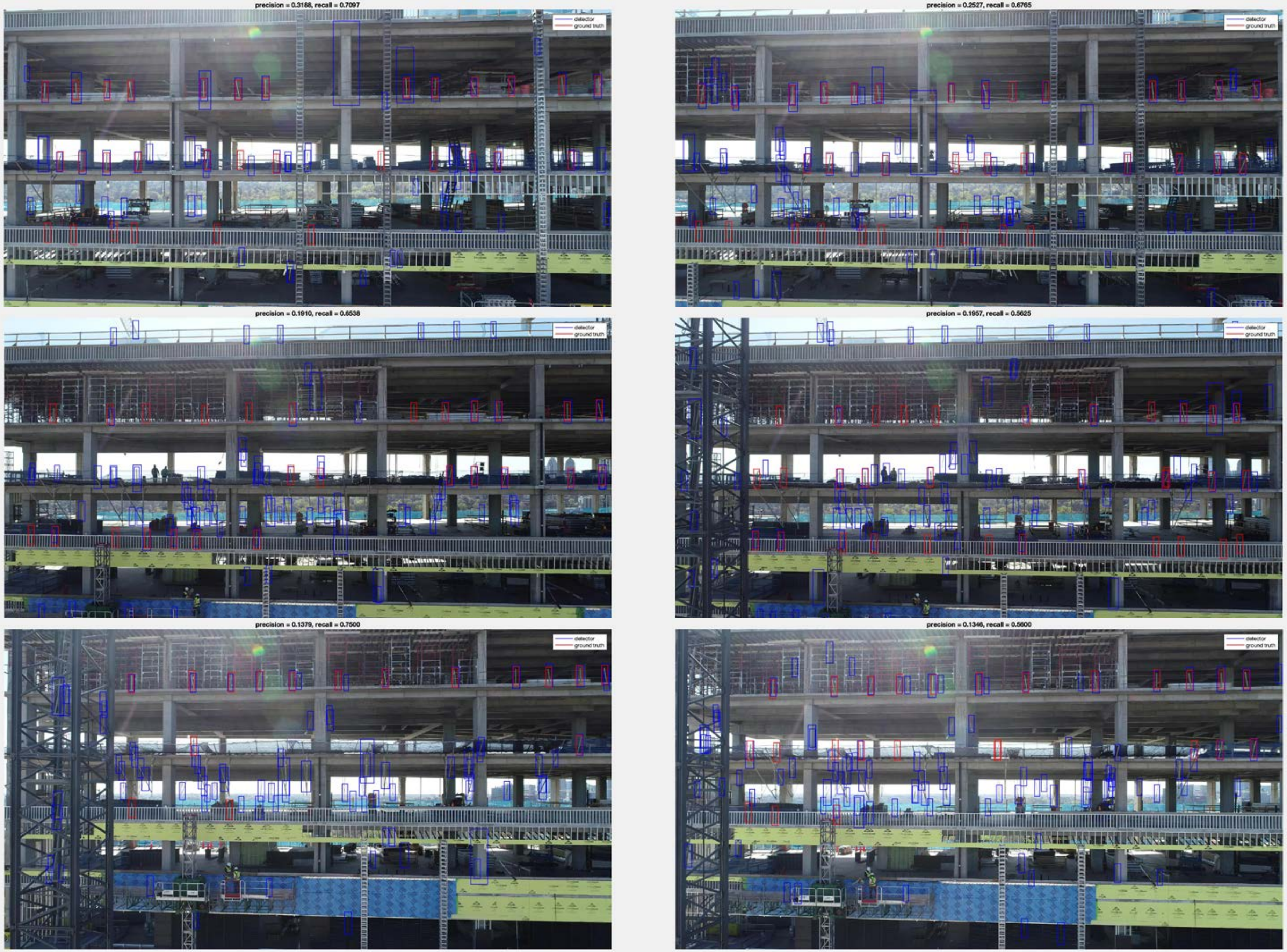
Drone4Safety

Drone Customizations

- *Enhancing PCD accuracy*
- ***Automated hazard identification***
- *Making Drone flights safer*
  - *e.g., Drone recovery systems + Super Optical Zoom Capabilities*

A three-step framework

(1) Guardrail detection
(2) Floor detection
(3) Space estimation



__Masoud Gheisari__, Behzad Esmaeili, Jana Kosecka, and Abbas Rashidi. 2020. Using Unmanned Aerial Systems for Automated Fall Hazard Monitoring in High-rise Construction Projects. Report for the Center for Construction Research and Training (CPWR). 1-17. https://www.cpwr.com/wp-content/uploads/publications/SS2020-Unmanned-Aerial-High-rise-Construction.pdf

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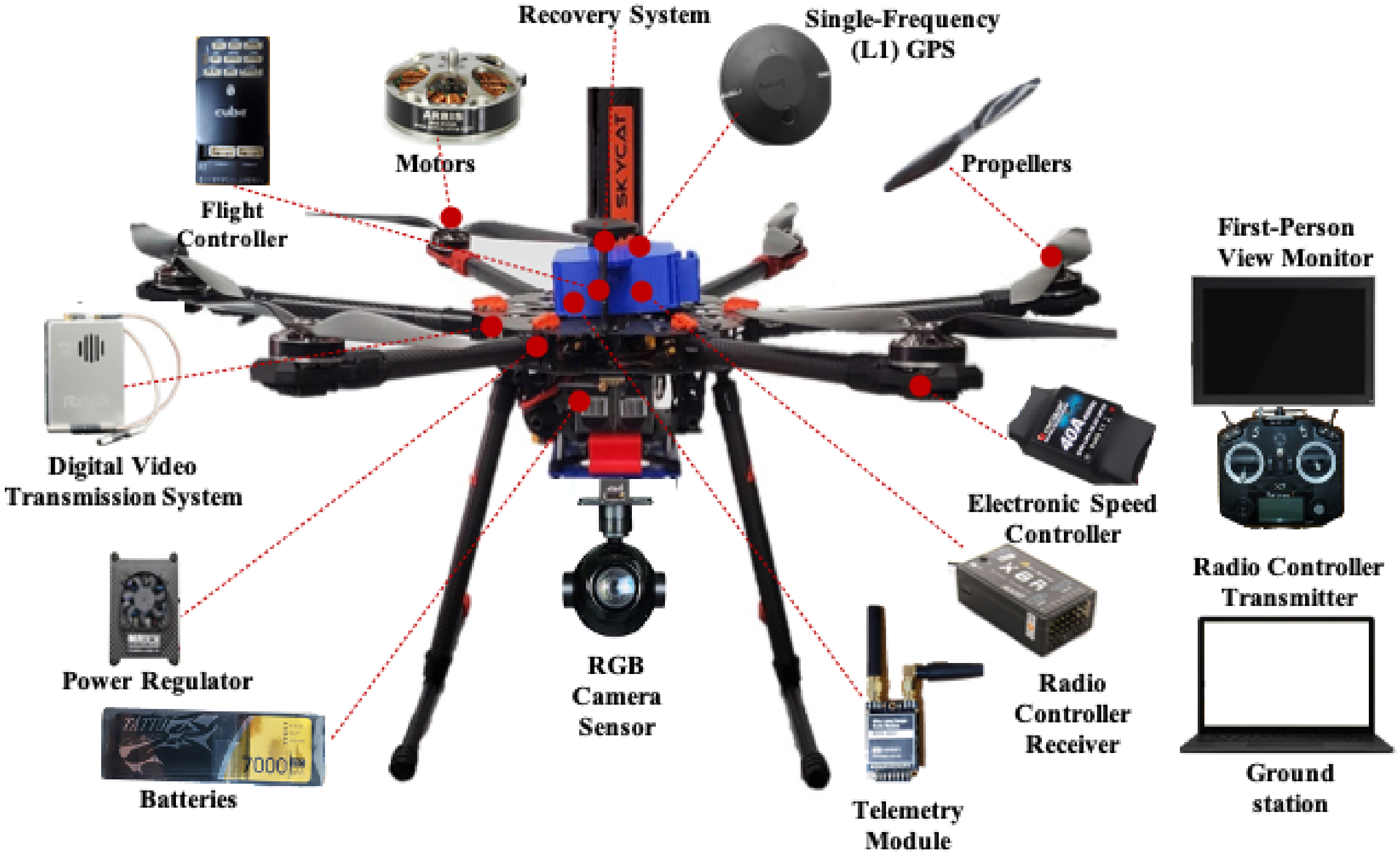
2010-2018 2019 2020 2021 2022

iSafeUAS

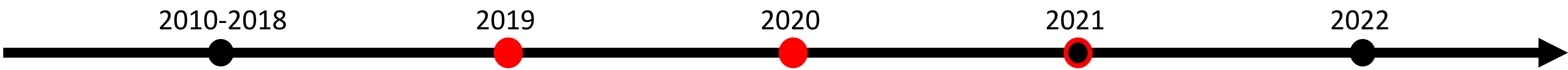
Making Drone flights and data collection safer

Parachute Recovery System

Super Optical Zoom Capability

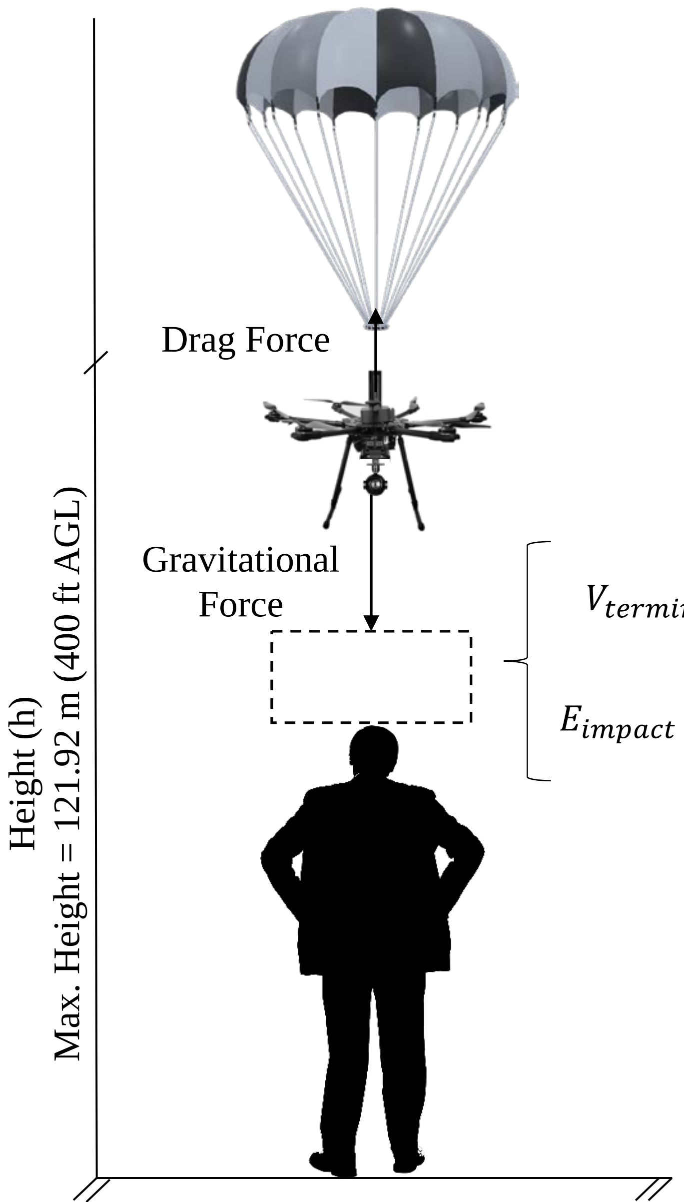


*Jhonattan G. Martinez(g), Gilles Albeaino(g), **Masoud Gheisari**, Raja R. A. Issa, and Luis F. Alarcón. 2020. iSafeUAS: An Unmanned Aerial System for Construction Safety Inspection. Elsevier Journal of Automation in Construction. 125: https://doi.org/10.1016/j.autcon.2021.103595*



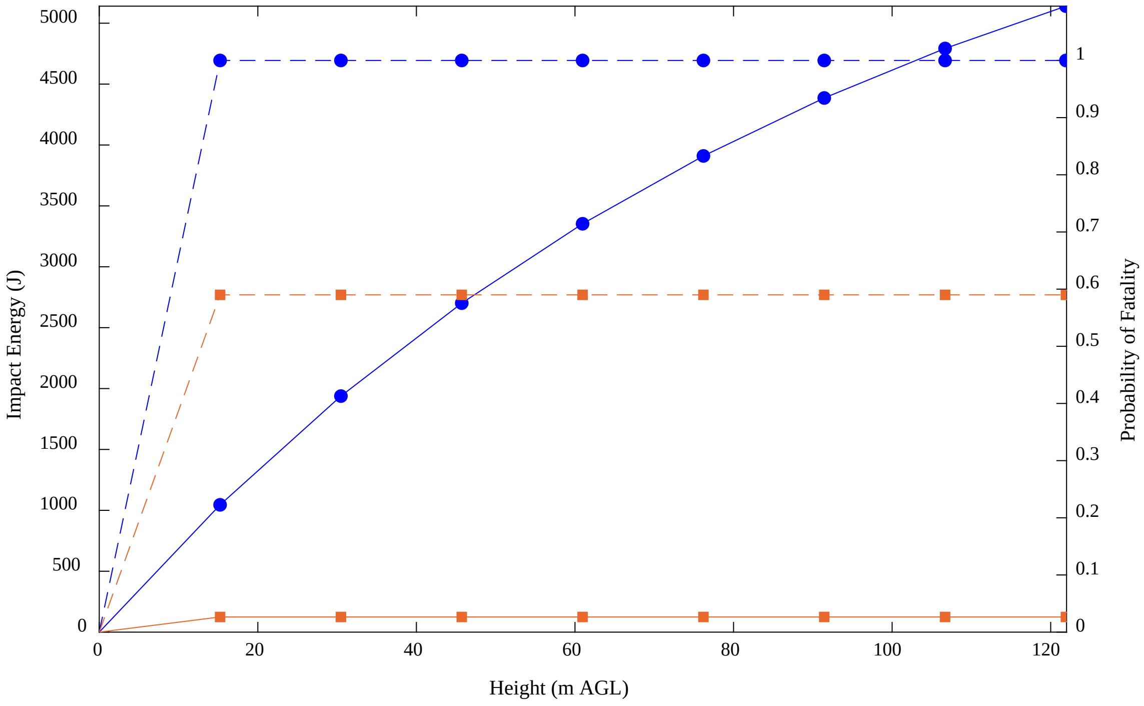
iSafeUAS

Making Drone flights and data collection safer



$$V_{terminal} = \sqrt{\frac{2mg}{C_d A \rho_A}}$$

$$E_{impact} = \frac{1}{2} m {V_{terminal}}^2 \left(1 - e^{\frac{-2gh}{{V_{terminal}}^2}}\right)$$

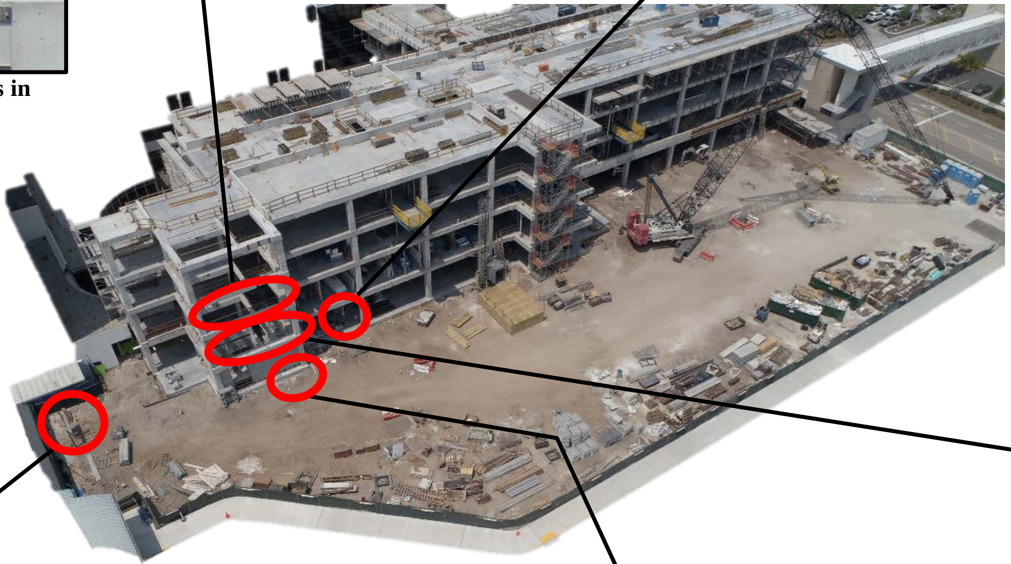


iSafeUAS

Potential safety hazards identified with 20X zooming capability

Fall Hazard: Improper installation of guardrails in some indoor openings

Tripping Hazard: Improper indoor housekeeping



Electrical Hazard: Improper warning signs around the electrical panel

Tripping Hazard: Uneven site surfaces

Struck-by Hazard: Improper storage of material located in indoor areas

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Safety4Drone

Safety Challenges of Worker-Drone Interactions

National Robotics Initiative 2.0:
Ubiquitous Collaborative Robots (NRI-2.0)

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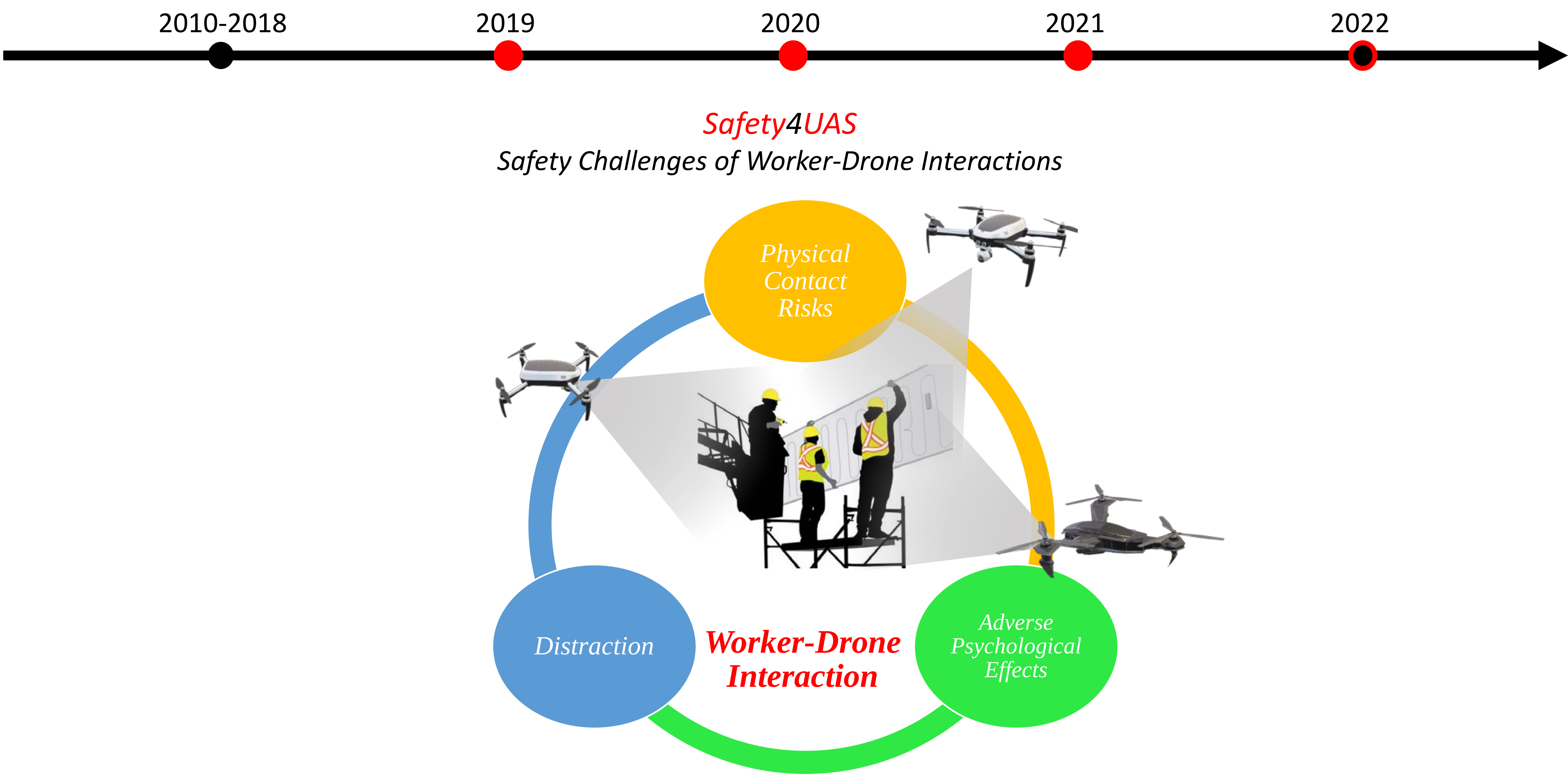


*Idris Jeelani, and **Masoud Gheisari.** 2021. Safety Challenges of UAV Integration in Construction: Conceptual Analysis and Future Research Roadmap. Elsevier Journal of Safety Science. 144: 1-16. https://doi.org/10.1016/j.ssci.2021.105473*

2010-2018 | 2019 | 2020 | 2021 | 2022

Safety4Drone

Safety Challenges of Worker-Drone Interactions

Physical Risks

- Struck by flying object
- Struck by falling object
- Struck by swinging object

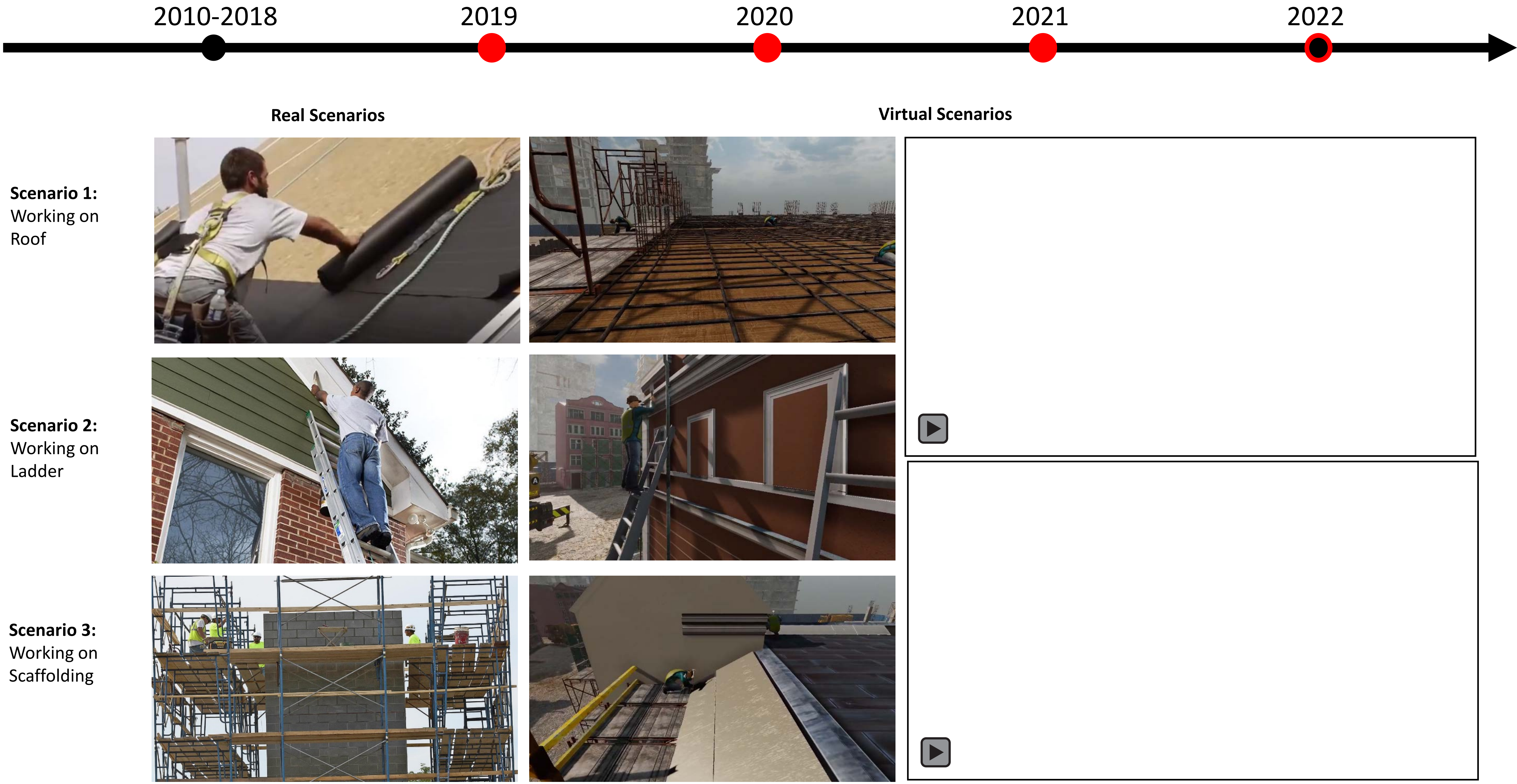
Attentional Cost

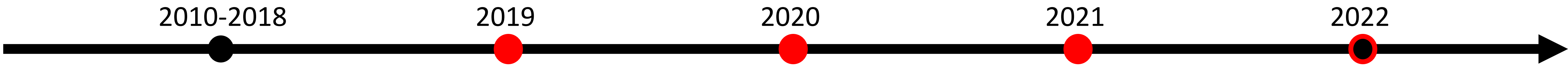
- Visual distraction
- Cognitive distraction
- Balance control deterioration

Psychological Impacts

- Acute stress
- Cognitive overload
- Sensory saturation
- Negative emotional State

*Idris Jeelani, and **Masoud Gheisari.** 2021. Safety Challenges of UAV Integration in Construction: Conceptual Analysis and Future Research Roadmap. Elsevier Journal of Safety Science. 144: 1-16. https://doi.org/10.1016/j.ssci.2021.105473*


2010-2018
2019
2020
2021
2022
Real Scenarios
Virtual Scenarios
Scenario 1:
Working on
Roof
Scenario 2:
Working on
Ladder
Scenario 3:
Working on
Scaffolding

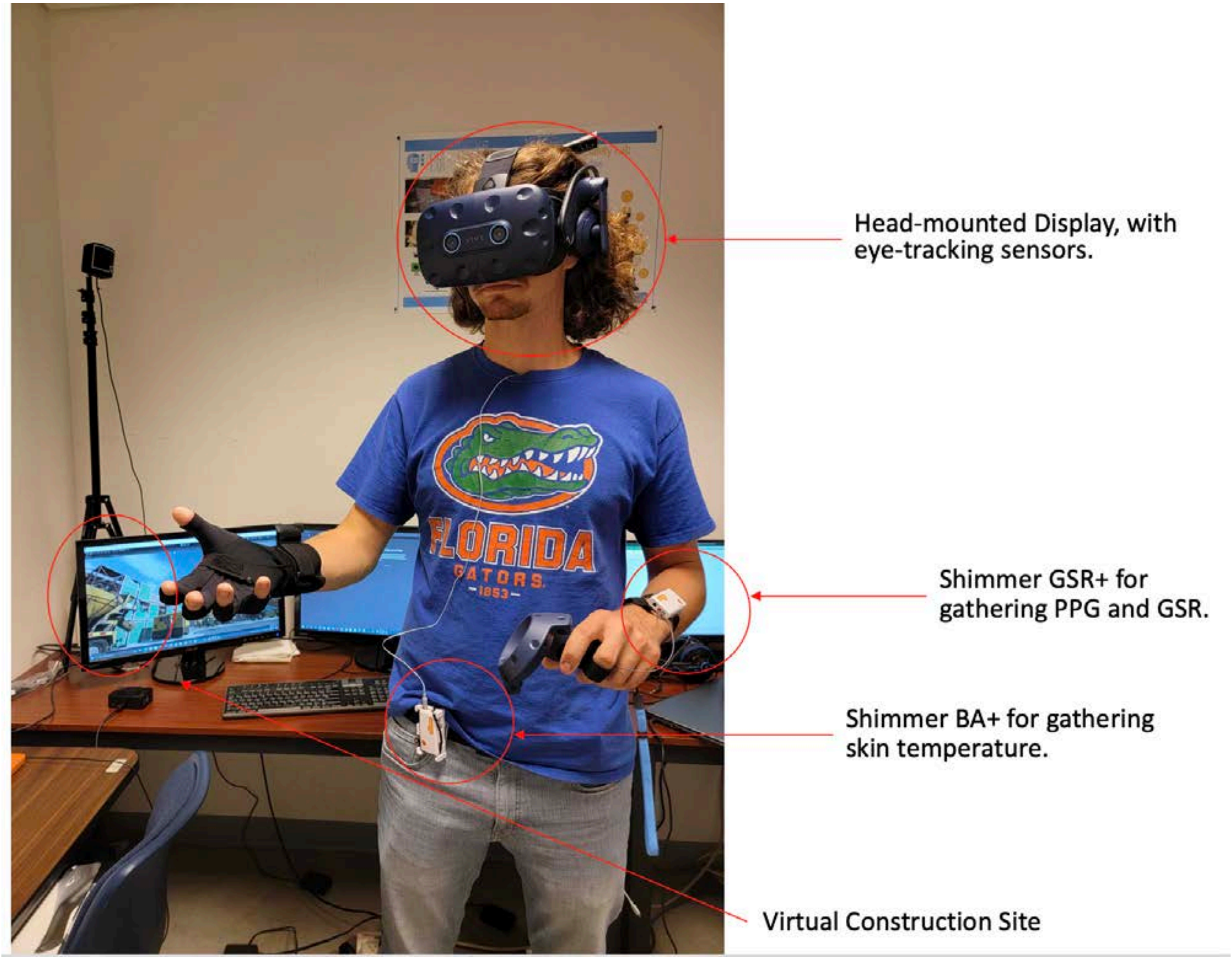


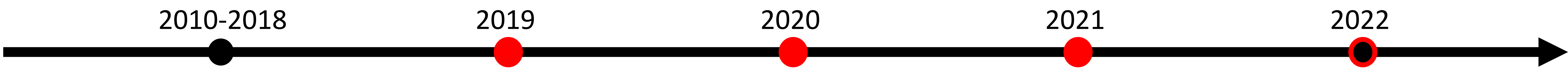
Experiment Design:

- Control Condition – VR Scenarios without Drones
- Experimental Condition – VR Scenarios with Drones

Assessment Methods and Measures:

- Job Performance
- Attentional Cost Measures
- Balance Control Measures
- Psychological Impact Measures
- Perceived Safety and Attitude Towards Robotics Peers



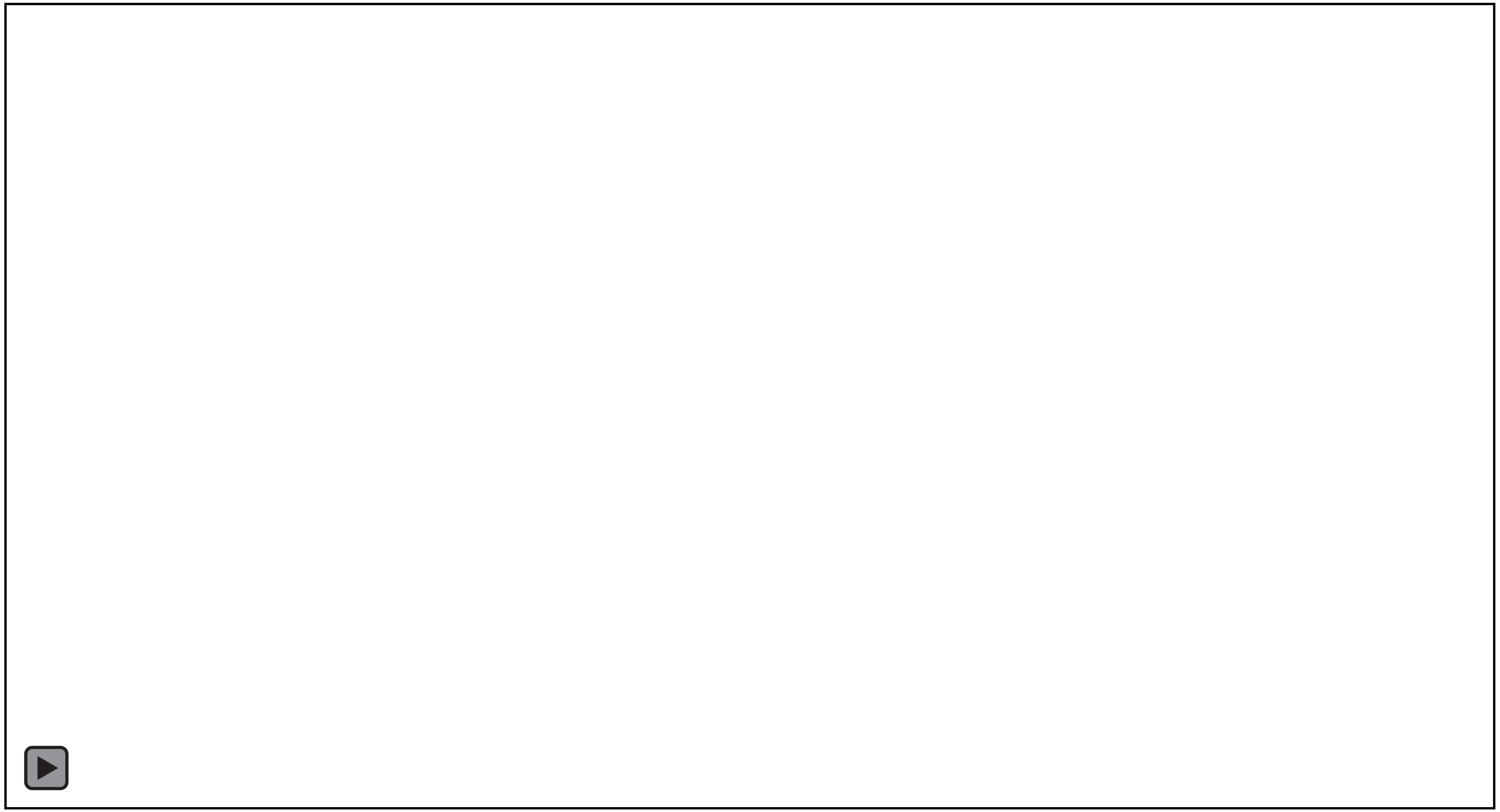


Simulation Variables

- ❑ **Flight Speed**
  - ❑ Construction applications
  - ❑ Drone Capabilities
- ❑ **Flight Altitude**
  - ❑ FAA Regulations
  - ❑ Construction applications
  - ❑ Literature
- ❑ **Drone Failure Rate (Randomized)**
  - ❑ Human Error
  - ❑ Technical Error
  - ❑ Environmental factors

Measures

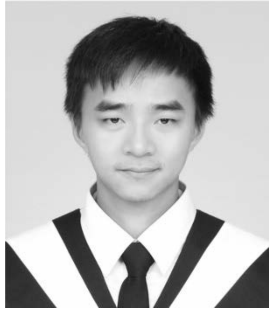
- ➢ Drone – Drone Collision
- ➢ Drone Building Collision
- ➢ Drone-Worker Collision
- ➢ Drone-Ground Collision
- ➢ Near-misses for above



Physical Contact Measures: Incident rate, # of drone contacts with virtual humans, # of payload or drone part contact with the virtual worker, # of drone contacts with structure/ other equipment, # of drone-drone collisions, # of near misses, # of incursions into worker or equipment safety envelope.

Our current team working on these projects:

Gilles Albeaino
BCN PhD Student



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Our Drone-related research sponsors:

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Thank you for your attention!!

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A Practical Model to Measure and Mitigate Safety Risks of Using UAS in Construction

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Oregon State University

Yiye Xu, PhD Student
School of Civil Construction Engineering
Oregon State University

March 23, 2022

UAS Applications in Construction

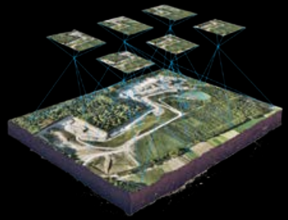
Time efficiency

Affordability

Ease of use

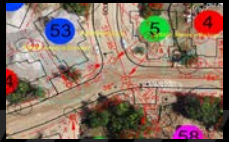
Access to hard-to-reach areas

- Pre-construction

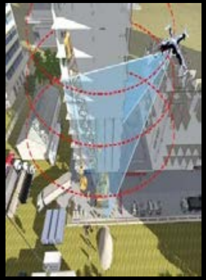


Mapping and Surveying

Site Layout Planning



- Construction



Security Surveillance

Progress/Quality/Safety monitoring

Logistics management

Site communication

Maintain social distancing

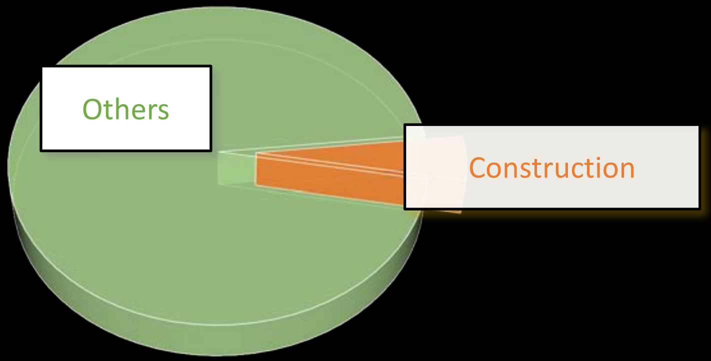
- Post-construction

As-built Documentation

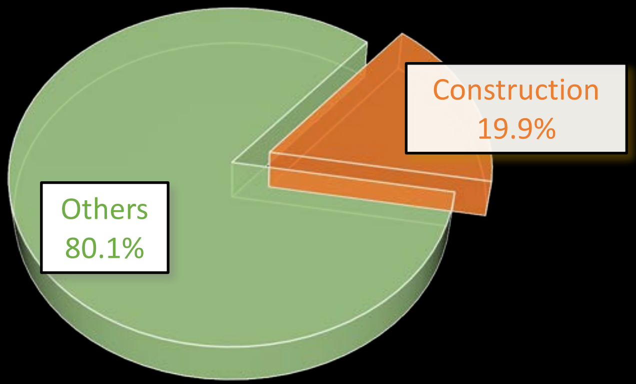
Structural inspection

Safety Concerns of the Use of UAS in Construction

PERCENT DISTRIBUTION OF U.S. WORKFORCE IN 2018[1]

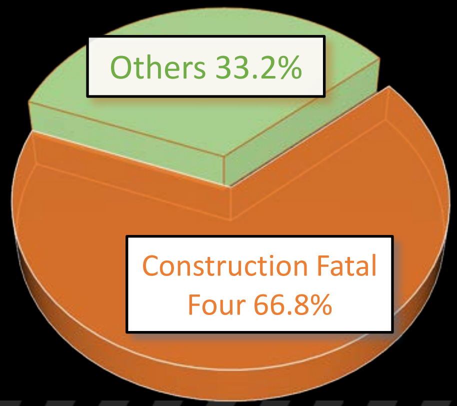


U.S. WORKER FATALITY RATE IN 2019[1]



1061 Fatalities

TYPE DISTRIBUTION OF CONSTRUCTION WORKER FATALITY IN 2019[1]



Potential Incident Scenarios:

- Crash/Collision
- Distraction
- Psychological and Physical Stress

Worsen the safety performance

Source: [1] U.S. Bureau of Labor Statistics (BLS 2019)

Research Objectives and Methods

Objective #1:
Identify causal factors of OSH risks associated with the UAS use in construction

Literature Review

Objective #2
Verify the potential causal factors leading to identified OSH risks

Objective #3
Quantify and verify the importance level of the verified causal factors

Objective #4
Identify and quantify the potential mitigation strategies for each of the causal factors.

Three-round Delphi Method

Goal:

Objective #5
Develop a practical model to assess the safety level of UAS use in construction

Literature Review – *Causal Factors (OB#1)*

UAS-Related Factors

- *Weight*
- *Speed*
- *Noise Level*
- *Feature Sophistication and Performance*
- *Inspection and Maintenance*

Mission-Related Factors

- *Distance to Structure/Workers*
- *Altitude*
- *Task Procedure*

Jobsite-Related Factors

- *Worker Density*
- *Obstacle*
- *Equipment/Vehicle Traffic*

Environment-Related Factors

- *Temperature*
- *Moisture*
- *Wind*
- *Illumination*
- *Air Space Conditions*

Contractor-Related Factors

- *Responsibility Classification*
- *Management Support Level*
- *UAS Safety Education/Training Program*

Flight Crew-Related Factors

- *Qualification and Experience*
- *Safety Record*
- *Team Communication*
- *Mental and the Physiological States*

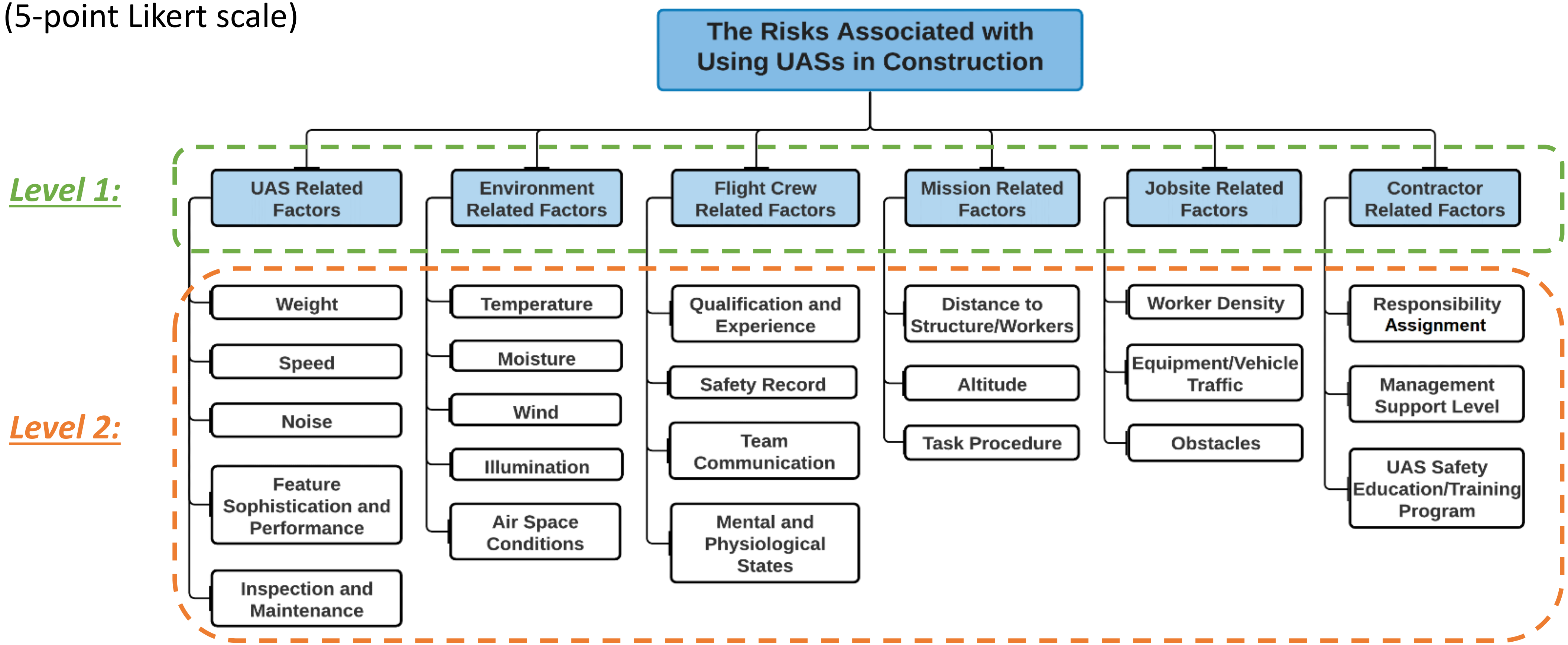
Delphi - *Round #1 (OB#2)*

Survey Questions

- Background information
- Any supplementary factors or concerns
- Level of agreement on identified causal factors (5-point Likert scale)

Survey Purpose

- Expert selection and qualification
- Verify the causal factors that could lead to identified OSH risks



Delphi - *Round #1 (OB#2)*

➢ Expert Selection and Qualification

Academics

Industry Professionals

Criteria (Score) / Participants	Professional Experience (1/year)	Advanced Degree (4/BS, 6/MS, 10/Ph.D.)	Publication (2/Journal, 2/Book or Book Chapter, 0.5/Conference Paper, 0.5/Industry Publication)	Member of a Committee (1/Committee)	Leadership Position (3/Each)	Conference Presentation (0.5/Presentation)	Professional Registration (3/Registration)	Total Score (Minimum 11)
1	10	PhD	J:18, BC: 4, CP:16, IP:4	2	0	10	2	87
2	13	PhD	J:32, BC:1, CP48, IP:10	4	2	45	1	153.5
3	31	PhD	J:84, BC:7, CP:73, IP:57	2	2	>150	1	374
4	25	PhD	J:79, BC:12, CP:140, IP:16	1	0	>190	0	391
5	12	PhD	J:21, BC:1, CP:15, IP:10	1	0	15	1	90
6	10	PhD	J:4, CP:4	0	0	8	0	34
7	1.5	PhD	J:7, CP:10	3	0	7	2	43
8	9	PhD	J:13, CP:16	3	0	13	0	62.5
9	12	PhD	J:4, BC:1, CP:10, IP:1	2	2	5	2	54
10	18	BS	0	2	1	5	2	35.5
11	22	MS	J:1	1	0	2	1	35
12	10	BS	0	1	0	2	0	16
13	38	BS	0	3	0	15	2	58.5
14	10	BS	IP:6	0	0	0	2	23
15	23	MS	IP:3	0	2	3	1	41
16	25	BS	0	1	4	30	2	63
17	4	MS	J:2	2	3	8	1	32
18	13	BS	J:2, IP:2	2	1	25	2	45.5
19	6	BS	0	1	0	7	0	14.5

Note: Criteria and score system used in this table is adapted and modified from Hallowell and Gambatese (2010)

Delphi - *Round 1 (OB#2)*

- 17 responses were used
- Descriptive statistics of level of agreement on identified causal factors
- SD < 1.5 was considered to indicate that the consensus was reached

Category	Causal Factors	Median	Average Rating (σ)	Category	Causal Factors	Median	Average Rating (σ)
UAS Related Factors	Weight	4.00	4.00 (0.92)	UAS Related Factors	Temperature	4.00	3.62 (1.24)
	Speed	4.00	3.88 (0.98)		Moisture	4.00	4.25 (0.71)
	Noise	4.00	3.38 (1.45)		Wind	5.00	4.63 (0.52)
	Feature Sophistication and Performance	4.00	3.75 (1.01)		Illumination	4.00	3.63 (1.10)
	Inspection and Maintenance	4.00	3.80 (0.85)		Air Space Condition	4.00	4.13 (0.64)
Mission Related Factors	Distance to Structures/Workers	4.00	4.13 (0.99)	Flight Related Factors	Qualification and Experience	4.00	4.10 (0.62)
	Altitude	4.00	3.80 (1.21)		Safety Record	4.00	3.87 (1.02)
	Task Procedure	4.00	4.13 (1.30)		Team Communication	4.00	3.87 (1.02)
Jobsite Related Factors	Worker Density	4.00	3.75 (1.02)		Mental and Physiological States	4.00	4.13 (0.64)
	Equipment/Vehicle Traffic	4.00	3.50 (1.07)	Contractor Related Factors	Responsibility Classification	4.00	4.25 (1.04)
	Obstacles	4.00	4.00 (0.76)		Management Support Level	4.00	3.88 (0.99)
					UAS Safety Education/Training Program	4.00	3.60 (1.3)

Note: 1 = Strongly Disagree, 5 = Strongly Agree (*N = 17)*

Delphi - *Round 2 (OB#3)*

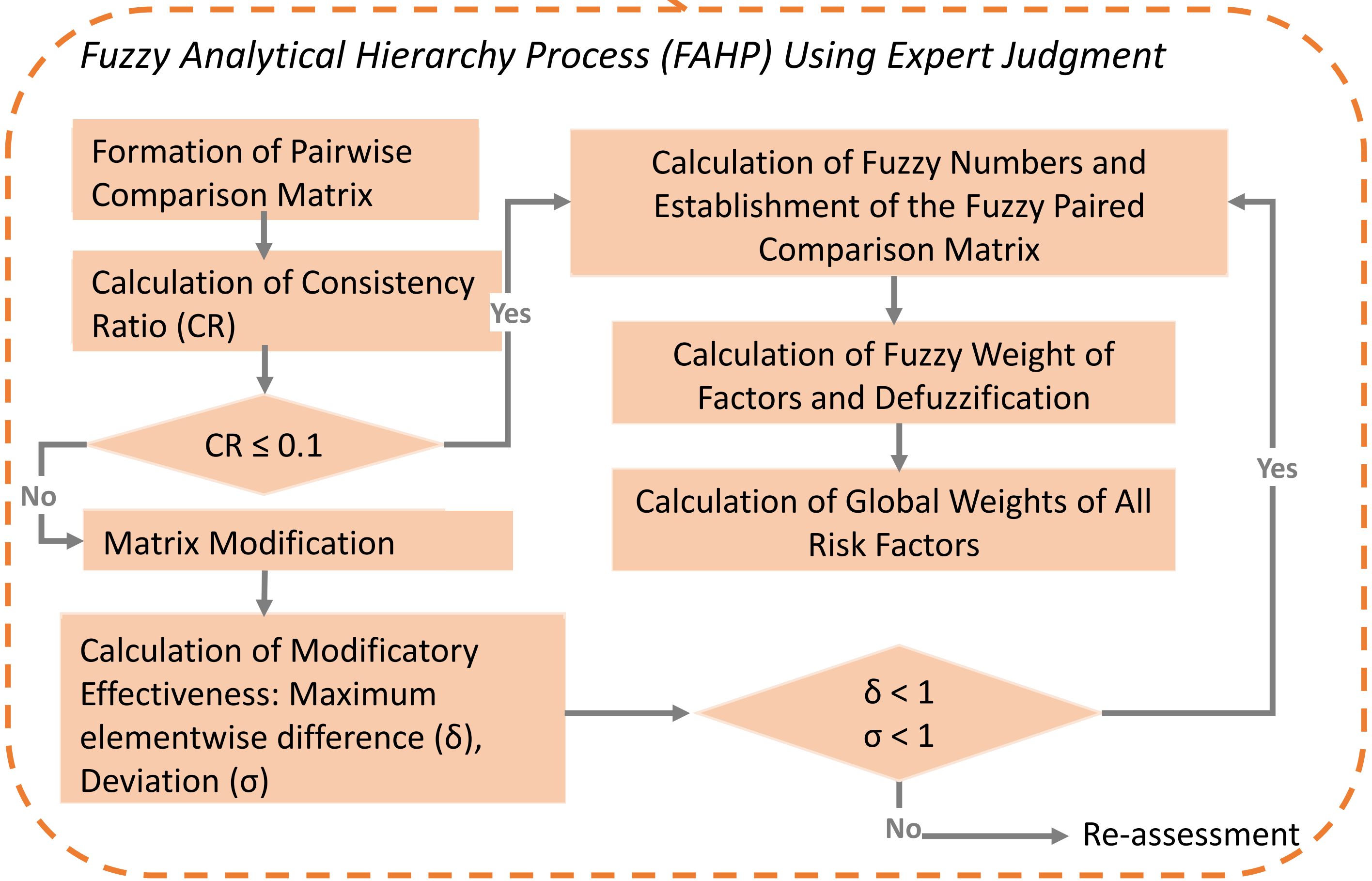
Survey Questions

- Relative importance based on overall safety impact using the linguistic scale
  - Level 1 factors (1 pairwise comparison table)
  - Level 2 factors (6 pairwise comparison tables)

Scale	Importance Level
1	Equally Important
1/3, 3	Slightly Less Important, Slightly More Important
1/5, 5	Moderately Less Important, Moderately More Important
1/7, 7	Strongly Less Important, Strongly More Important
1/9, 9	Extremely Less Important, Extremely More Important

Survey Purpose

- Prioritization of causal factors



Delphi – *Round 2 (OB#3)*

- All 17 responses reached satisfied CR condition.
- Prioritization of causal factors (top six)
  - *- Wind*
  - *- Weight*
  - *- Inspection and Maintenance*
  - *- Speed*
  - *- Distance to Structure/Workers*
  - *- Feature Sophistication and Performance*

Level 1 Risk Factors	Local Weight	Level 2 Risk Factors	Local Weight	Global Weight	Rank
UAS-Related Factors	0.265	Weight	0.233	0.0617	2
		Speed	0.215	0.0570	4
		Nosie	0.128	0.0339	18
		Feature Sophistication and Performance	0.188	0.0498	6
		Inspection and Maintenance	0.230	0.0610	3
Environment-Related Factors	0.226	Temperature	0.149	0.0337	19
		Moisture	0.146	0.0330	20
		Wind	0.318	0.0719	1
		Illumination	0.166	0.0375	14
		Air Space Conditions	0.208	0.0470	10
Flight Crew-Related Factors	0.172	Qualification and Experience	0.289	0.0497	7
		Safety Record	0.282	0.0485	9
		Team Communication	0.218	0.0375	15
		Mental and Physiological States	0.203	0.0349	16
Mission-Related Factors	0.115	Distance to Structures/Workers	0.435	0.0500	5
		Altitude	0.267	0.0307	21
		Task Procedure	0.298	0.0343	17
Jobsite-Related Factors	0.130	Worker Density	0.361	0.0469	11
		Equipment/Vehicle Traffic	0.305	0.0397	13
		Obstacles	0.334	0.0434	12
Contractor-Related Factors	0.092	Responsibility Classification	0.254	0.0234	22
		Management Support Level	0.216	0.0199	23
		UAS Safety Education/Training Program	0.530	0.0488	8

Note: *N = 17*

Delphi - *Round 3 (OB#4)*

Survey Questions

- Select and input mitigation methods for each of the causal factors
- Provide effectiveness rate for each mitigation method (1 = slightly effective, 3 = highly effective)

Survey Purpose

- Identify mitigation methods
- Quantify mitigation methods

4. (Features Sophistication and Performance) For mitigating the UAS safety risks to construction workers that are associated with UAS's feature sophistication and performance, what safety practices would you suggest to implement? **Please select all that apply** and **indicate effectiveness level of your selection(s) in the box (1 = slightly effective, 2 = moderately effective, 3 = highly effective).**

- [ ] Global Positioning System (GPS)
- [ ] Obstacle avoidance sensors on multiple sides of an UAS
- [ ] Return-to-Home (RTH) feature
- [ ] Geofencing (a feature that uses a UAS's GPS receivers to automatically enforce warnings or restrictions based on where the drone is flying)
- [ ] Autopilot systems (allow UAS to perform missions autonomously without the need for manual remote control)
- [ ] ADS-B technology (Automatic Dependent Surveillance-Broadcast), which gathers flight data sent automatically from nearby aircraft with ADS-B transmitters, analyzing it to detect potential collision risks and alert users well in advance through operation app (e.g., DJI AirSense))
- [ ] Others, please also specify their effectiveness level [ ]

Example Survey Question

Delphi - *Round 3 (OB#4)*

- 13 fully completed responses were used
- A mitigation method was retained if it was selected or brought up by 50% of experts (seven experts in our case)
- 74 mitigation methods were identified *(here only shows the mitigations for UAS-related factors)*

Effectiveness Level / Causal Risk Factors	Level 1	Level 2	Level 3
Weight	Equipping UAS with recovery systems (e.g., parachute systems and/or airbag system)	Choosing a lighter UAS meeting the requirement for a specific task	Compliance with FAA rules (UAS weight no more than 55 lbs)
Speed		Using a UAS that has a range of speed modes including a low-speed mode; Using a UAS equipped with blades protection (e.g., blade guards)	Compliance with FAA rules (UAS maximum speed is 100 mhp); Identification of the maximum operation speed for UAS for a specific task
Nosie	Provide ear protection equipment to onsite employees while UAS in operation	Choose a UAS with a minimum level of noise emmision based on the noise generated by the current construction work	
Feature Sophistication and Performance	ADS-B technology (Automatic Dependent Surveillance-Broadcast)	Autopilot systems	Global Positioning System; Obstacle aviodance sensors; Return-to-Home feature; Geofensing
Inspection and Maintenance		Join an aircraft maintenance program and schedule inspection and maintenance following manufacturer recommendations	Choose a UAS with a brand/manufacturer with a positive public/customer perception of quality and maintenance; Inspect the outer shell and other components for abnormalities such as damage or cracking before and after every flight

Note: Level 1 = Slightly Effective (1 point); Level 2 = Moderately Effective (2 points); Level 3 = Highly Effective (3 points), $N = 13$

Development of UAS Safety Assessment Model *(OB#5)*

Causal Factors (i) / Effectiveness Level (k) / (j)		Level 1	Level 2	Level 3	Performance Index
Level 1 Factors	**Level 2 Factors**	Risk Mitigation Available (RMA)			$PI_{ij} = \frac{\sum_{k=1}^{3} N(RMI_{ij})_{level_k} \times S(level_k)}{\sum_{k=1}^{3} N(RMA_{ij})_{level_k} \times S(level_k)}$ x 100
Local Weight for Level 1 Factors (LWi)	Local Weight for Level 2 Factors $(LWij)$				$PI_{total} = \sum_{i=1}^{6} \sum_{j=1}^{in} (PI_{ij} \times LW_i \times LW_{ij})$

Score	Safety Level	Diagnosis	Action
0 - 32	Low	Minimum safety level	Mitigation methods with higher effectiveness are needed to control some or all risk causal factors
33-67	Intermediate	Moderate safety level	Mitigation methods with higher effectiveness are needed to control some risk causal factors
67 - 100	High	Desirable safety level	Adjust as needed

Conclusions and Recommendations

- ✓ This study proposed a practical model that can be used for assessing the safety level of UAS utilization in the construction industry by performing a mixed-method approach – literature review and three-round Delphi process

- ✓ The components of the practical model are expected to enable practitioners working in the construction industry to
  (1) recognize the causal factors of OSH risks associated with the use of UAS in construction;
  (2) establish a procedure for selecting the proper UAS equipment with satisfactory quality and features for assisting with different tasks in construction; and
  (3) create safety control programs or adjust and update their own safety control programs, for UAS-assisted projects.

- ➢ The implementation and validation of the proposed model are beyond the scope of this study and future research is needed to assess and validate the proposed model for various UAS applications in construction.

THANK YOU !

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