TOOLS TO FACILITATE AUTONOMOUS QUADROTOR-BASED CINEMATOGRAPHY

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12/12/2016

QUADROTOR CAMERAS HAVE HUGE POTENTIAL IN MOVIEMAKING

[3DR Solo, 2015]

QUADROTOR CAMERAS LOWER COST OF AERIAL CINEMATOGRAPHY

Helicopter
Rent at >$1000 per hour

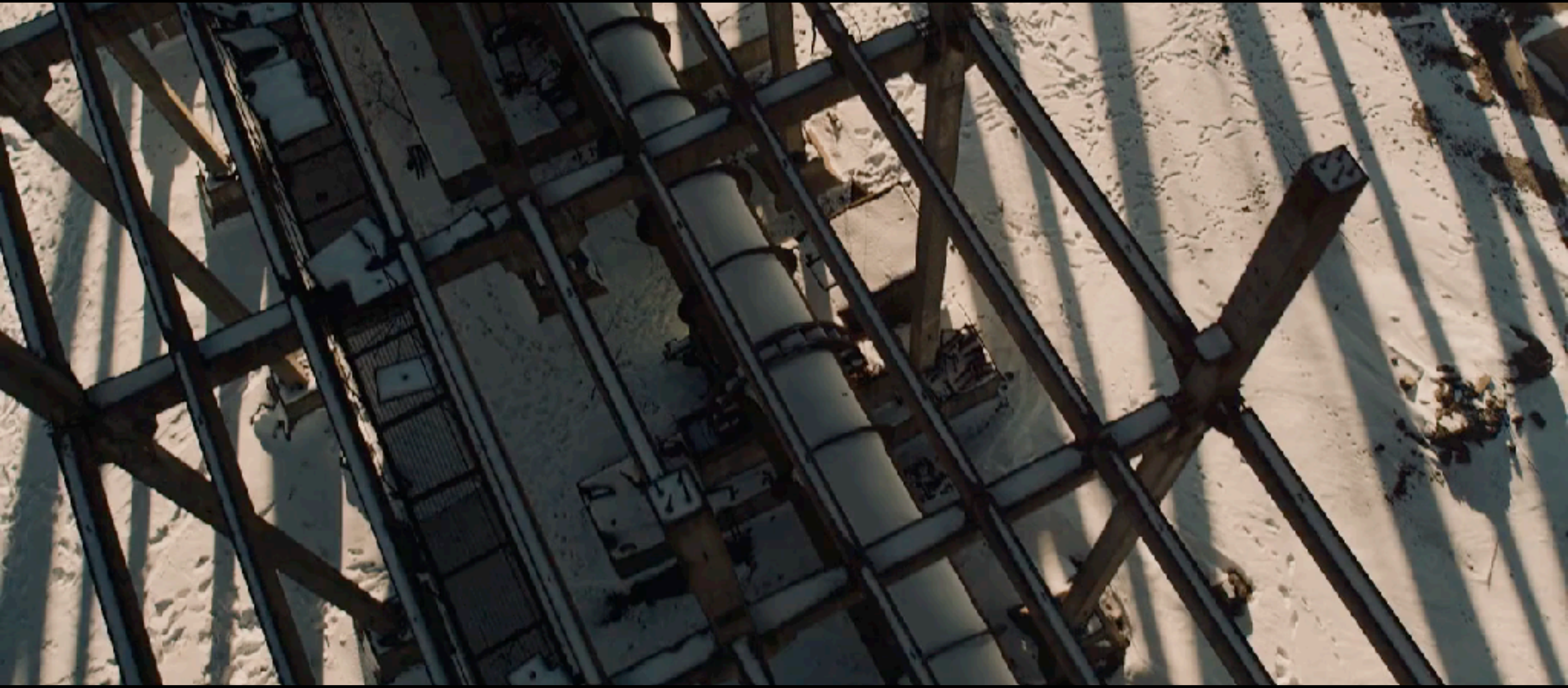
[Red Bull, 2014]

Quadrotor
Purchase for ~$1000

[Cut Media, 2014]

QUADROTOR CAMERAS SUBSUME OTHER CAMERA RIGS

QUADROTOR CAMERAS ENABLE NEW CINEMATOGRAPHY



AeroCine, “The Fallen”, 2015
NYC Drone Film Festival Award Winner

BUT REQUIRES CHALLENGING MANUAL OPERATION

[AeroCine]

PILOT CAMERAMAN

USING INTERFACES NOT DESIGNED FOR CINEMATOGRAPHY

DJI Controller, Peter Homer, 2015

Niels' Grandpa's Controller, 1989

PROBLEM

QUADROTOR CINEMATOGRAPHY
REQUIRES

TECHNICAL SKILL OF FLYING, AND
ARTISTIC SKILL OF COMPOSITION,
SIMULTANEOUSLY APPLIED IN REAL TIME

APPROACH

CINEMATOGRAPHY-FIRST INTERACTION

We will **automate the role of the pilot**

Provide tools that enables the user to
focus on the composition of shots

OVERVIEW

Compose shots using classic 3D Animation primitives, adapted to respect quadrotor camera physics [SIGASIA 2015]

Horus

A Tool for Shot Planning

Compose shots in real time using visual composition principles from filmmaking [arXiv 2016]

Drone Cinematographer

A Tool for Filming People

OVERVIEW

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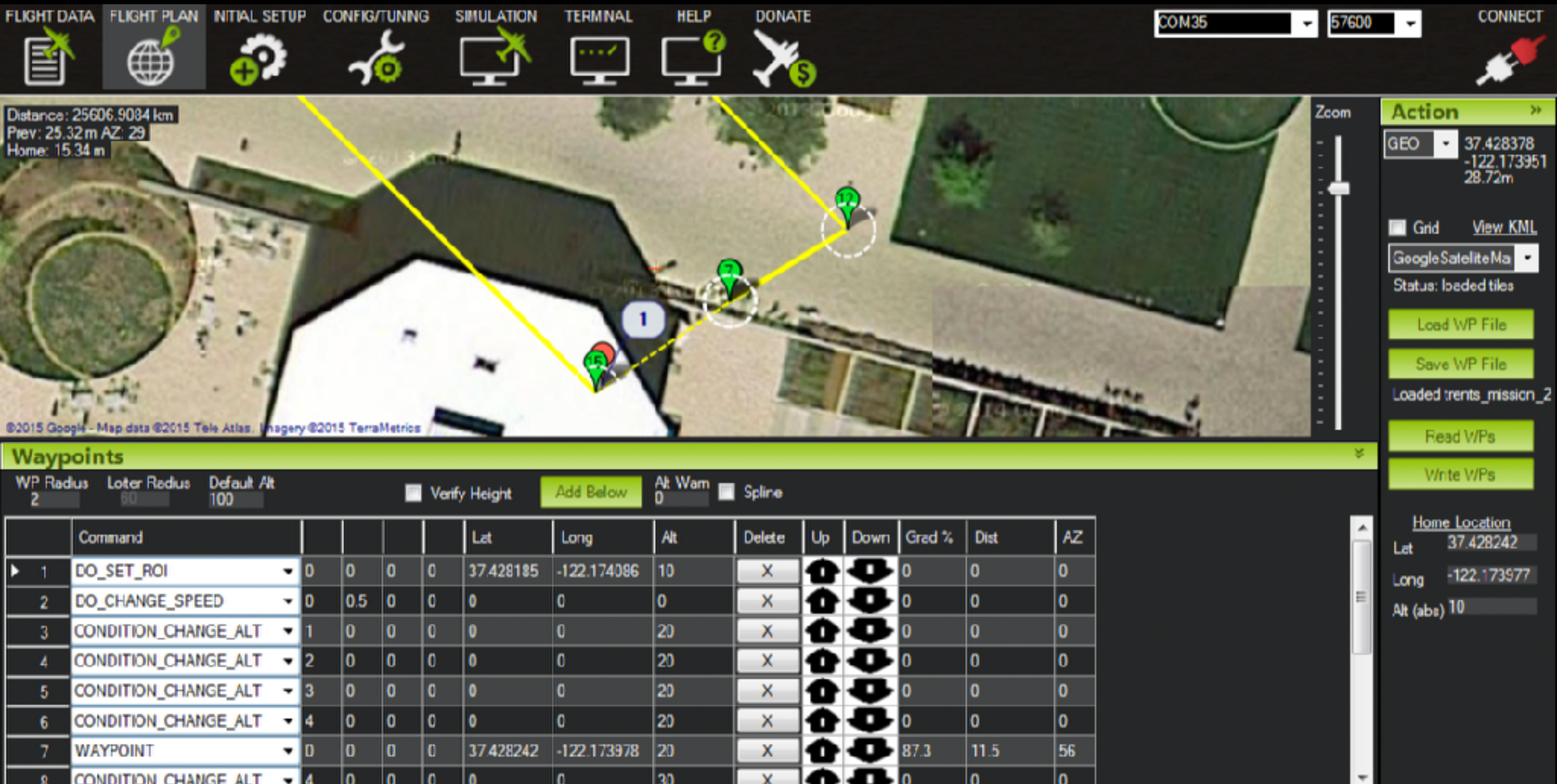
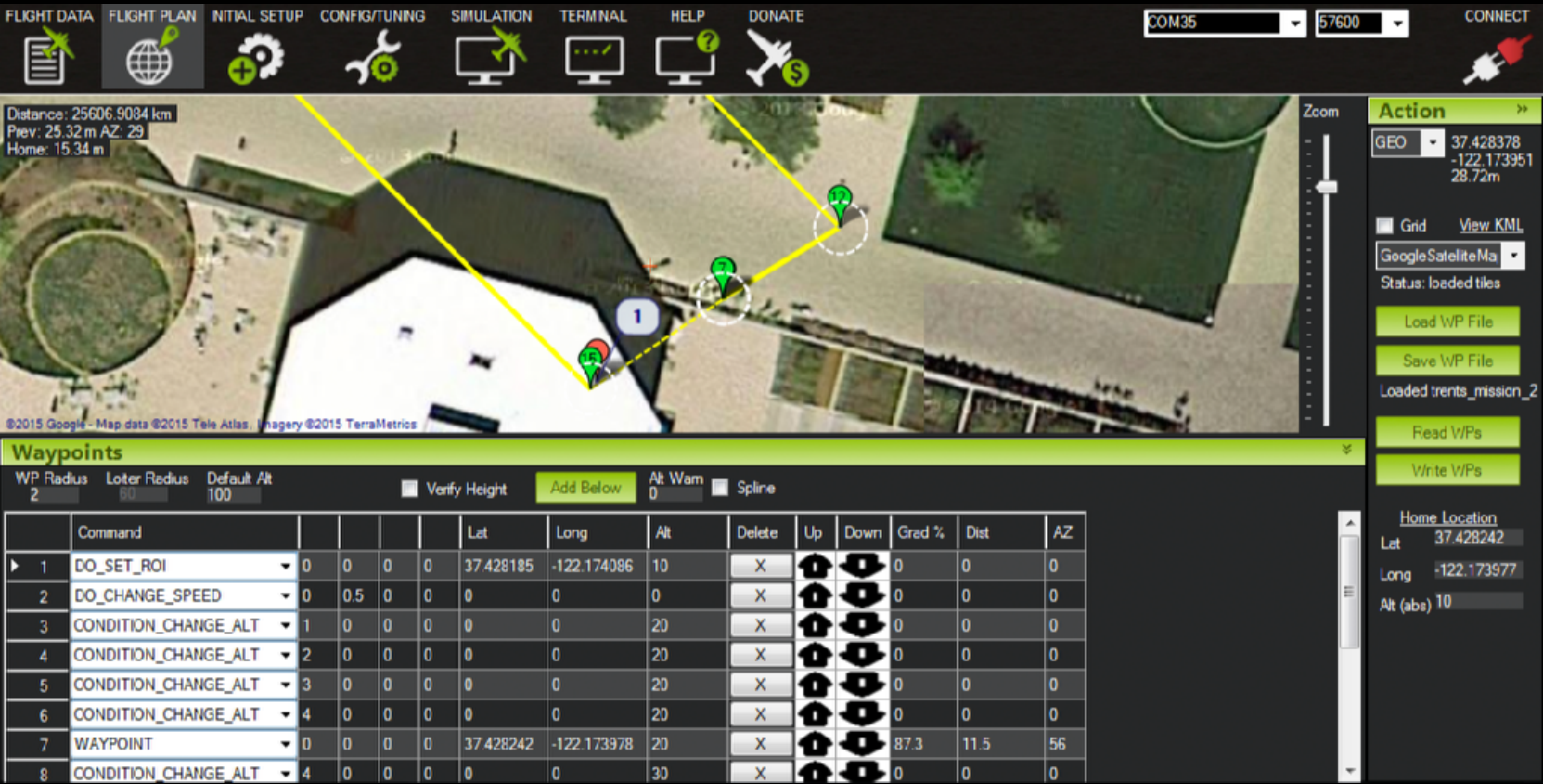
SHOT WITH HORUS

MISSION PLANNING TOOLS ALSO AUTOMATE THE PILOT



Mission Planner, ArduPilot, 2015

BUT THEY DO NOT ALLOW USERS TO FOCUS ON SHOT COMPOSITION



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2	DO_CHANGE_SPEED	0	0.5	0	0	0	0	0	X			0	0	0
3	CONDITION_CHANGE_ALT	1	0	0	0	0	0	20	X			0	0	0
4	CONDITION_CHANGE_ALT	2	0	0	0	0	0	20	X			0	0	0
5	CONDITION_CHANGE_ALT	3	0	0	0	0	0	20	X			0	0	0
6	CONDITION_CHANGE_ALT	4	0	0	0	0	0	20	X			0	0	0
7	WAYPOINT	0	0	0	0	37.428242	-122.173978	20	X			87.3	11.5	56
8	CONDITION_CHANGE_ALT	4	0	0	0	0	0	30	X			0	0	0

Mission Planner, ArduPilot, 2015

EXPLORATORY STUDY REVEALS CINEMATOGRAPHY CONCERNS

6 professional quadrotor photographers and videographers

Novice, Intermediate, and Expert skill levels

Are familiar with mission planning tools, but have not adopted them for cinematography.

HOW DO WE ALLOW USERS TO...

plan shots visually

precisely control shot timing

rapidly iterate on shots

see **accurate visual previews**

enable **autonomous capture**

USE 3D ANIMATION PRIMITIVES!

plan shots visually

precisely control shot timing

rapidly iterate on shots

see **accurate visual previews**

enable **autonomous capture**

[Real-Time Cameras, Haigh-Huchinson, 2009]
[Christie et al, 2008]

USE 3D ANIMATION PRIMITIVES!

plan shots visually ✓

precisely control shot timing ✓

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[Real-Time Cameras, Haigh-Huchinson, 2009]
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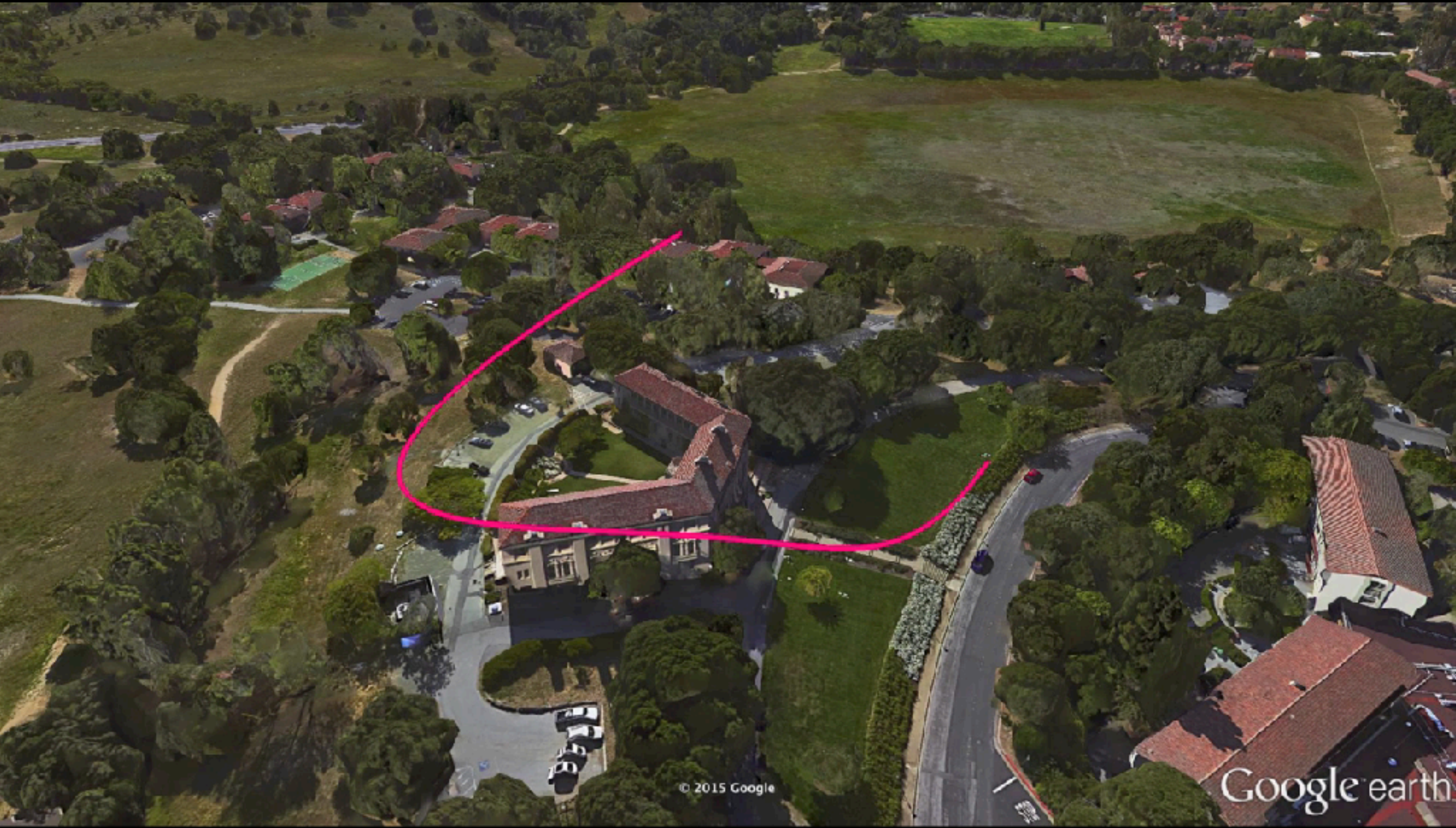
USE 3D ANIMATION PRIMITIVES!

- **plan shots visually** ✓
- **precisely control shot timing** ✓
- **rapidly iterate on shots** ✓
- see **accurate visual previews** ✗
- enable **autonomous capture** ✗

[Real-Time Cameras, Haigh-Huchinson, 2009]
[Christie et al, 2008]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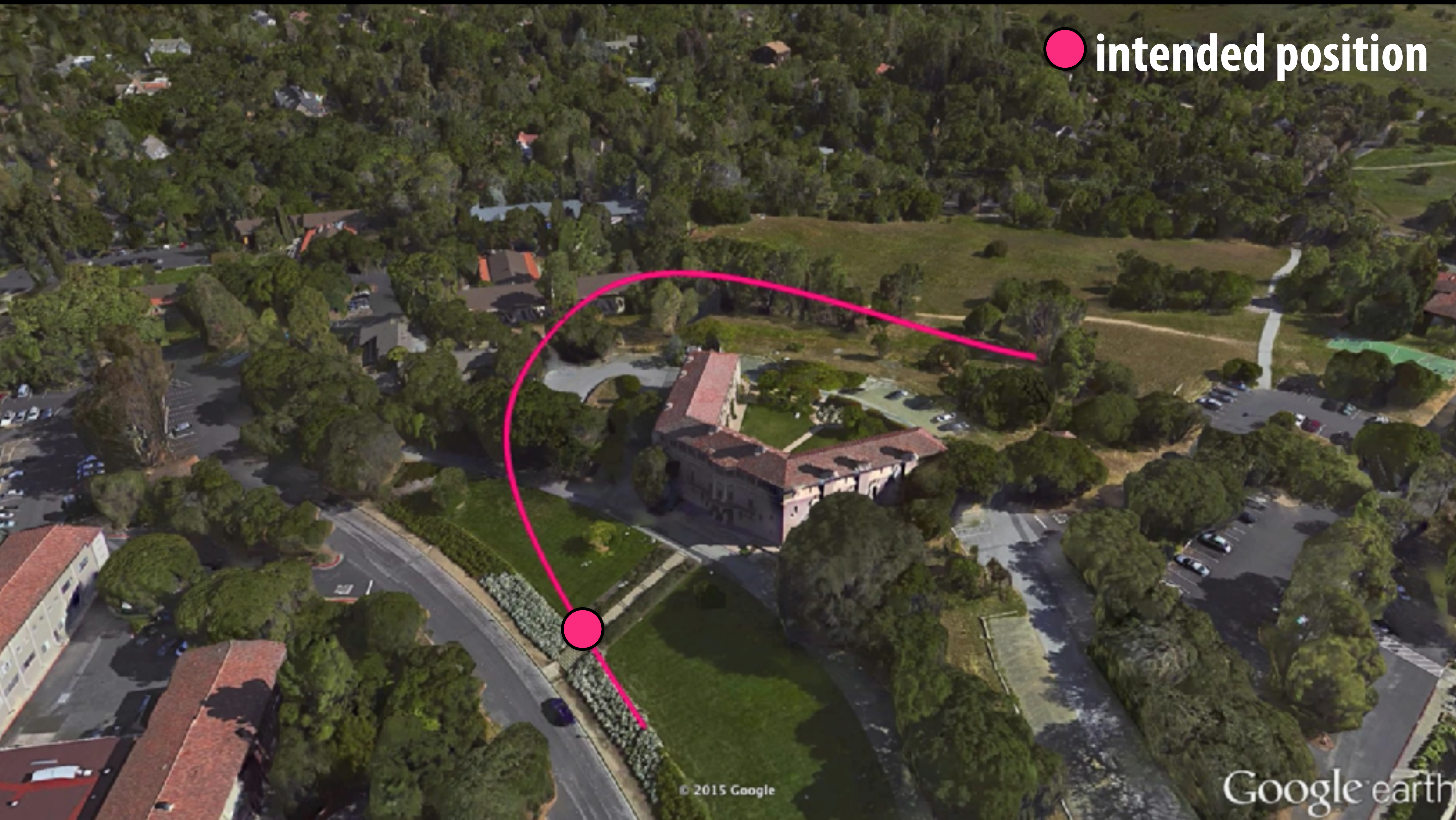
intended position
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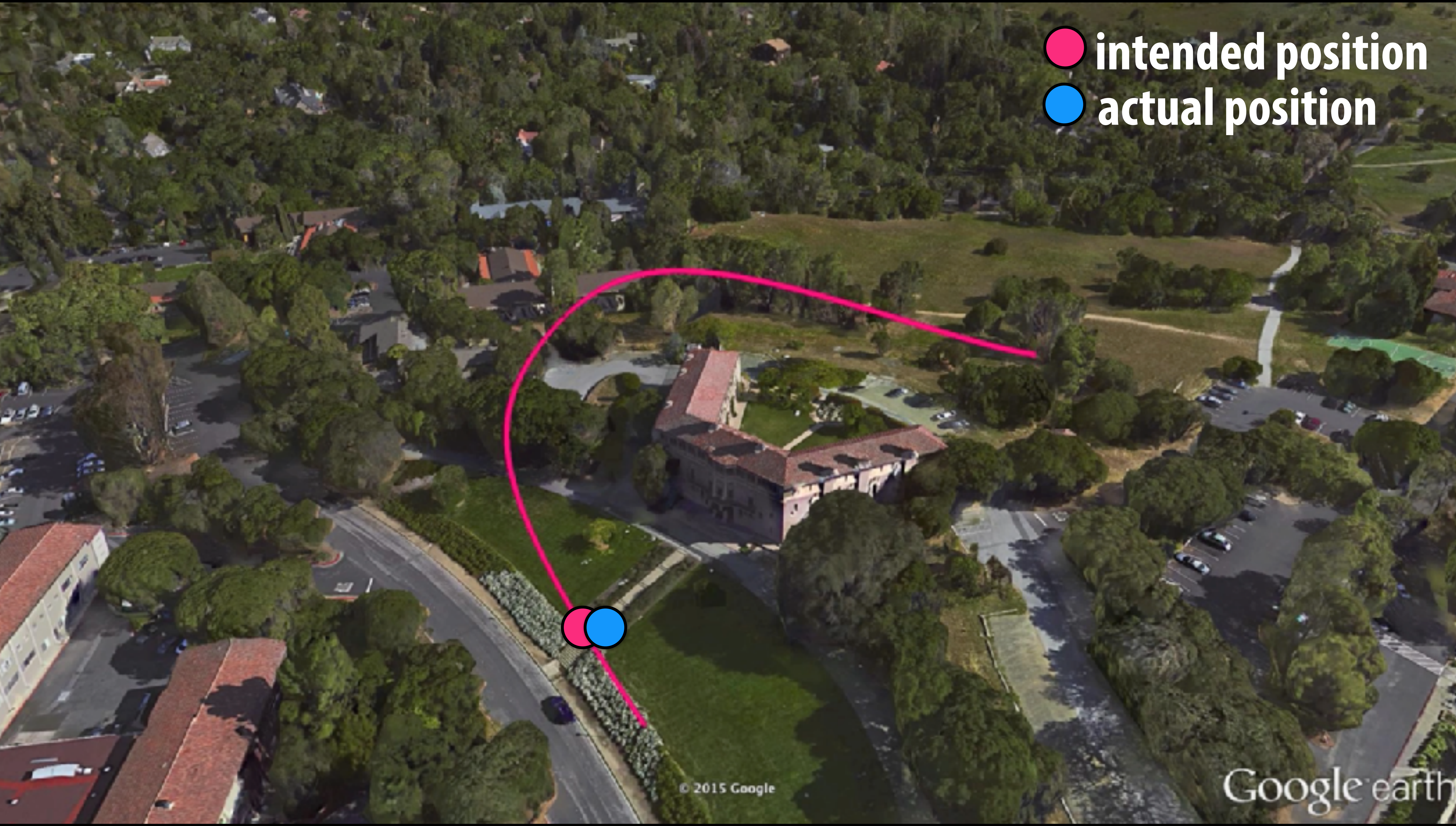
intended position
actual position
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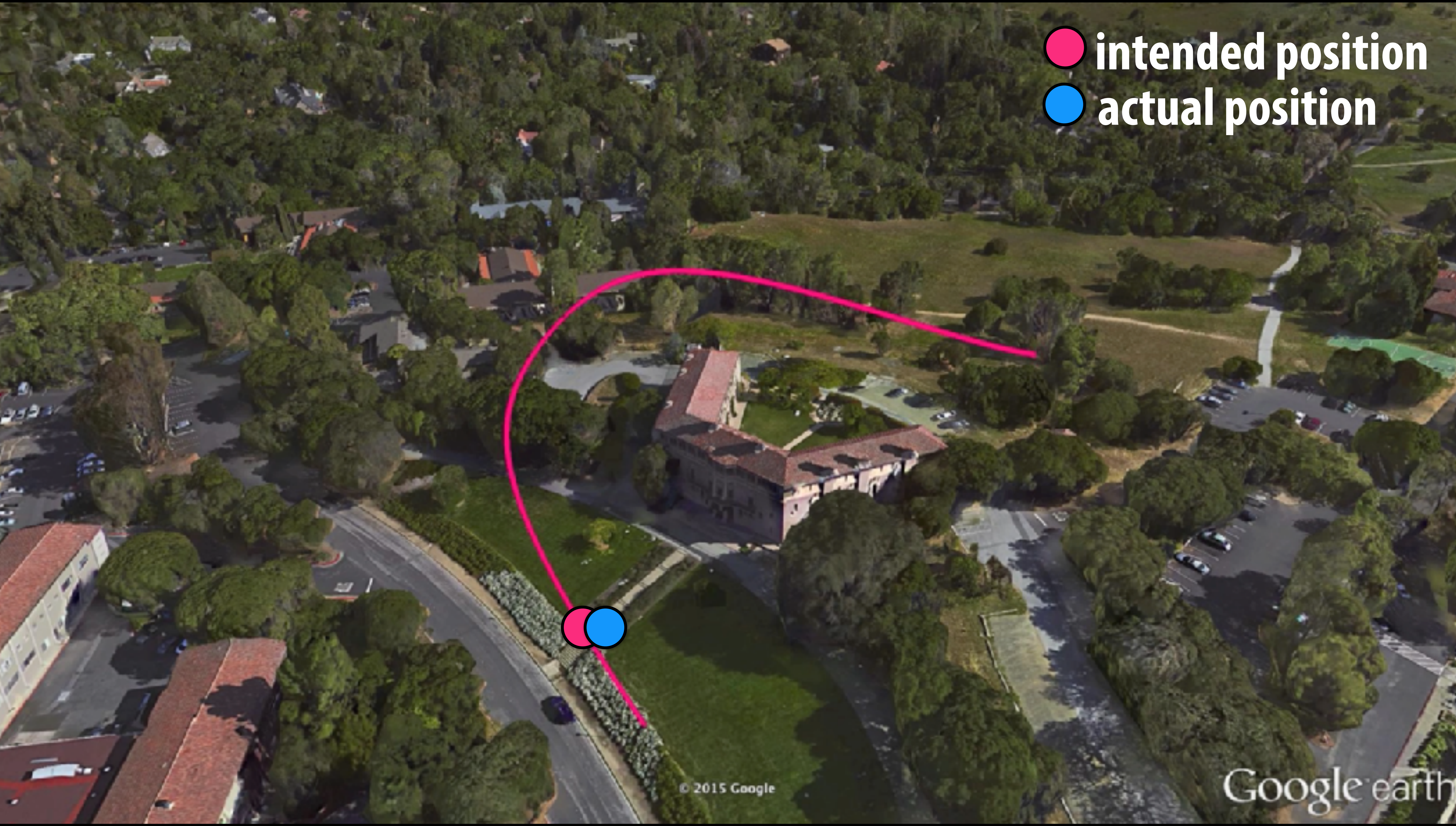
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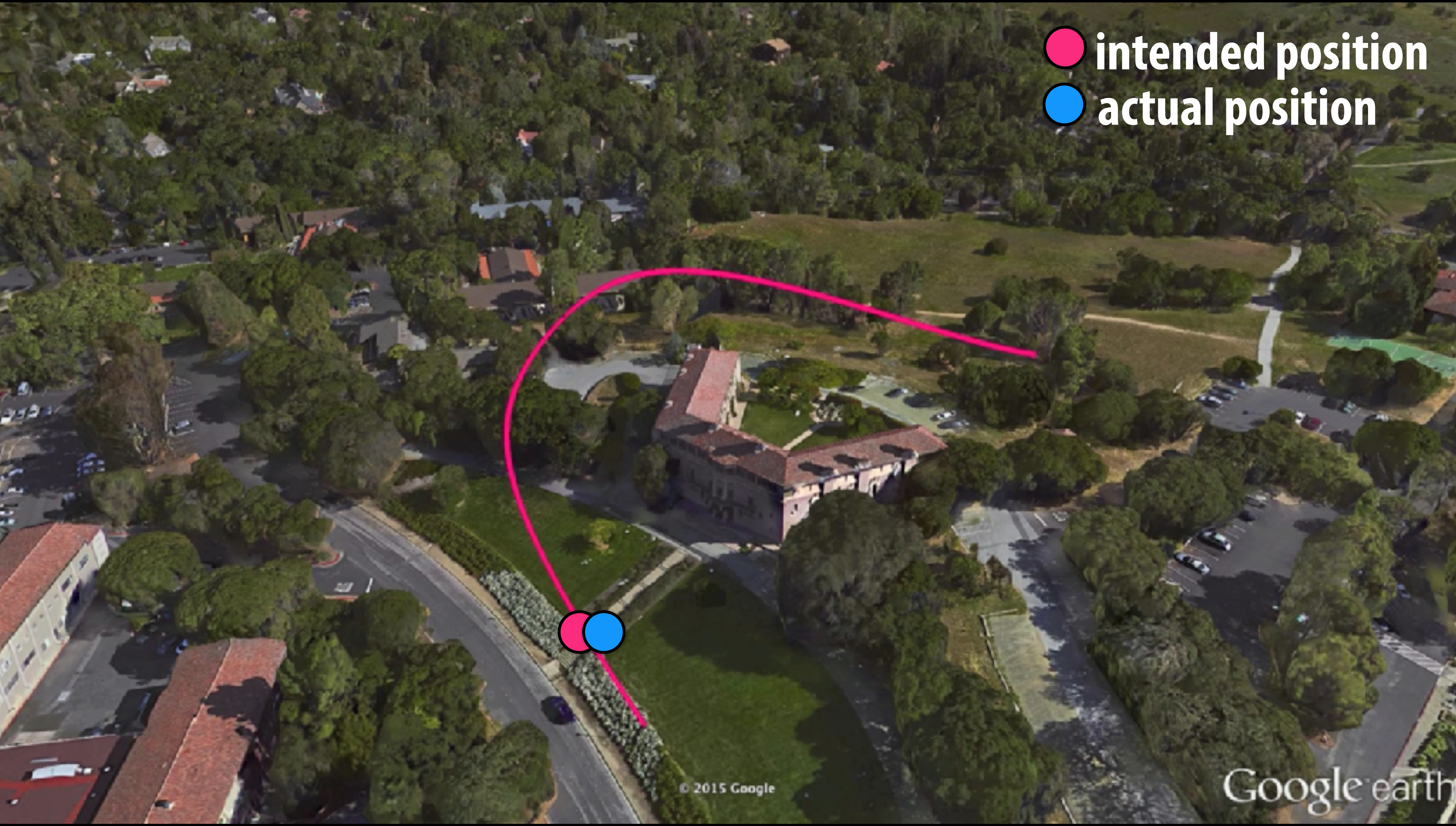
intended position
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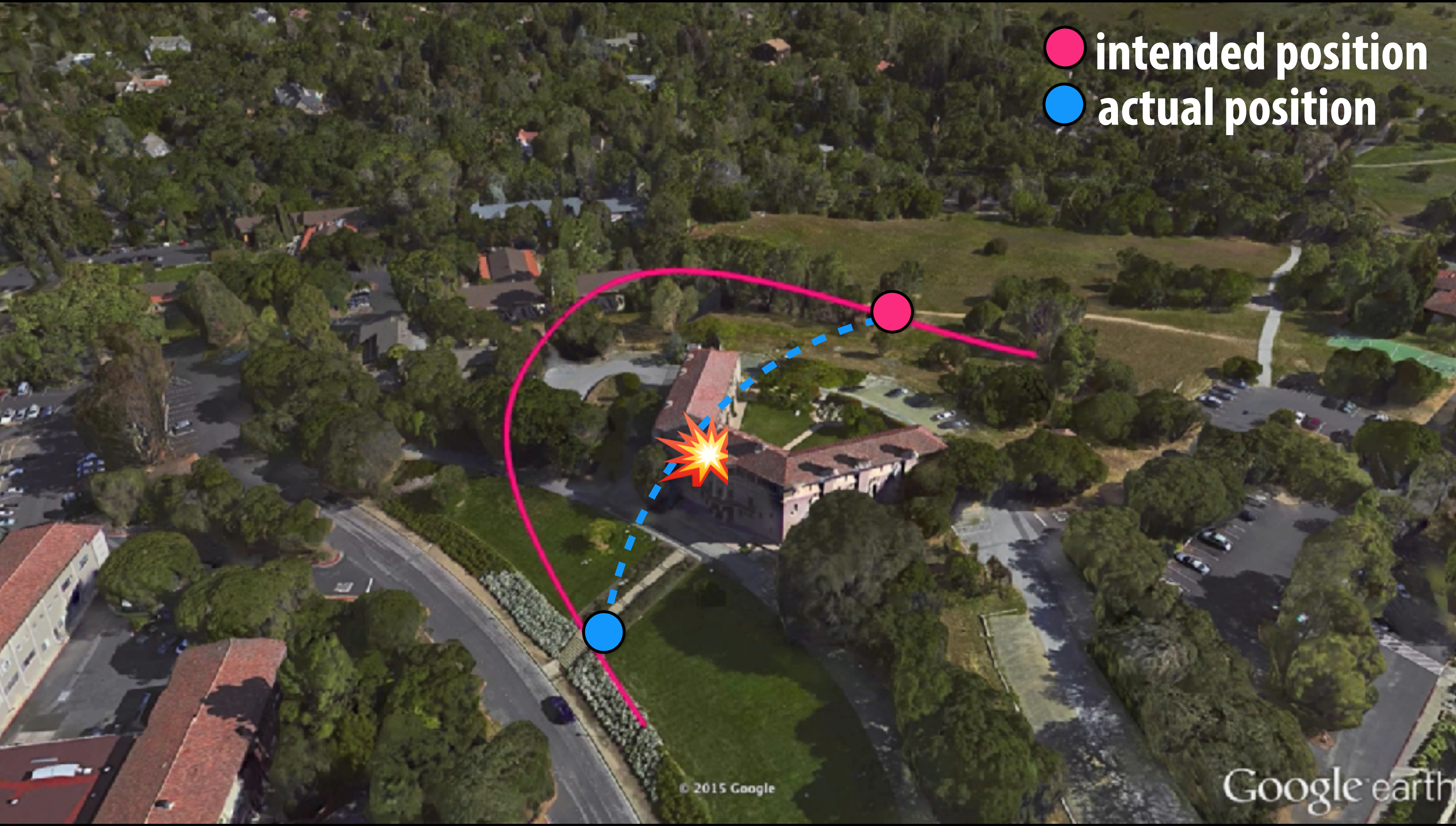
intended position
actual position
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APPROACH

Invent a **shot planning interface**
based on concepts from 3D Animation.

Adapt 3D Animation Primitives to respect quadrotor physics.

[Real-Time Cameras, Haigh-Huchinson, 2009] [Christie et al, 2008]

USE 3D ANIMATION PRIMITIVES!

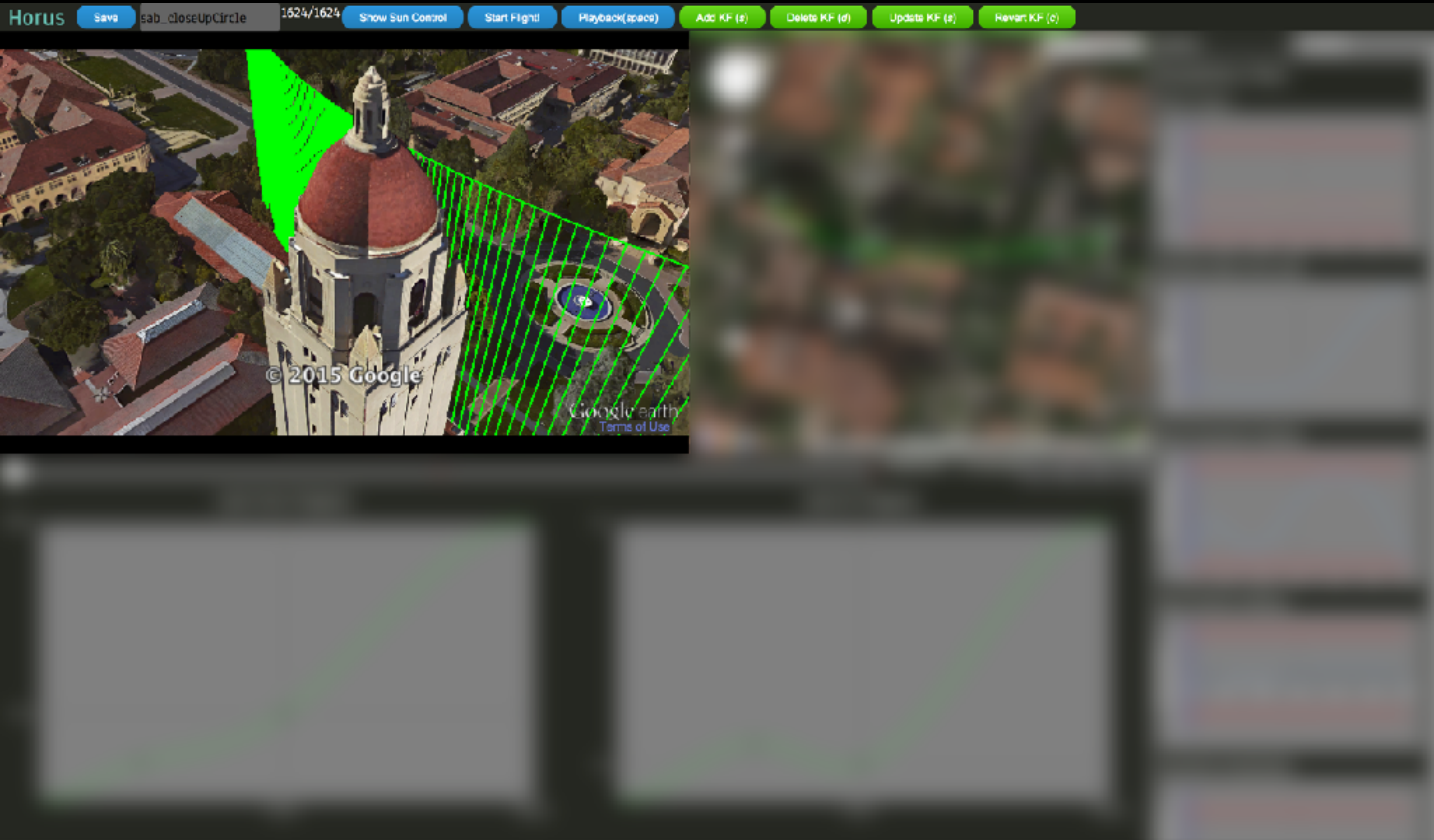
- **plan shots visually** ✓
- **precisely control shot timing** ✓
- **rapidly iterate on shots** ✓
- see **accurate visual previews** ✓
- enable **autonomous capture** ✓

USE 3D ANIMATION PRIMITIVES!

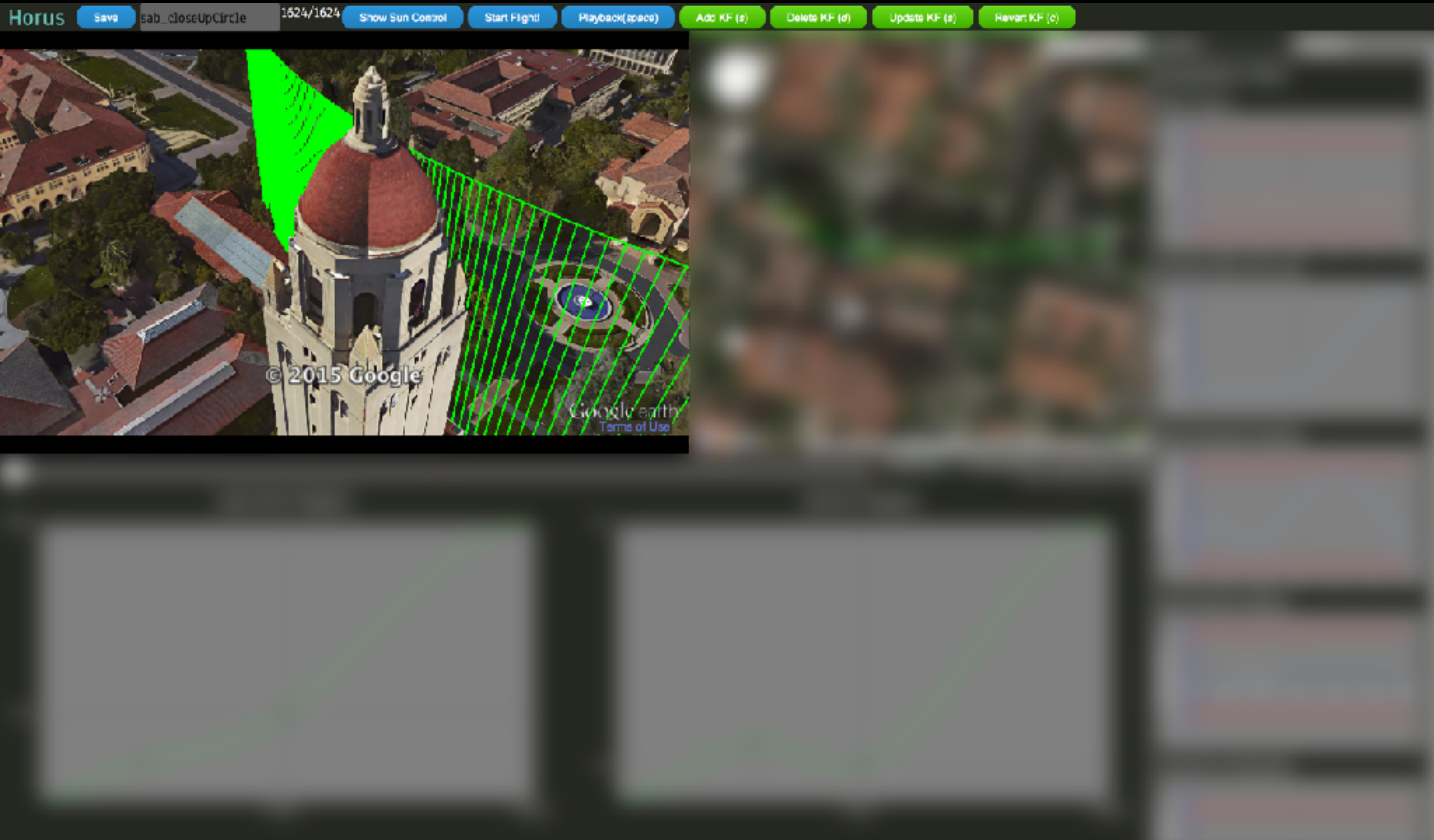
- **plan shots visually** ✓
- **precisely control shot timing** ✓
- **rapidly iterate on shots** ✓
- see **accurate visual previews** ✓
- enable **autonomous capture** ✓
- **provide feedback** about quadrotor behavior ✓

THIS IS HORUS

PLAN SHOTS VISUALLY IN A 3D ENVIRONMENT



PLAN SHOTS VISUALLY USING SPARSELY SPECIFIED KEYFRAMES



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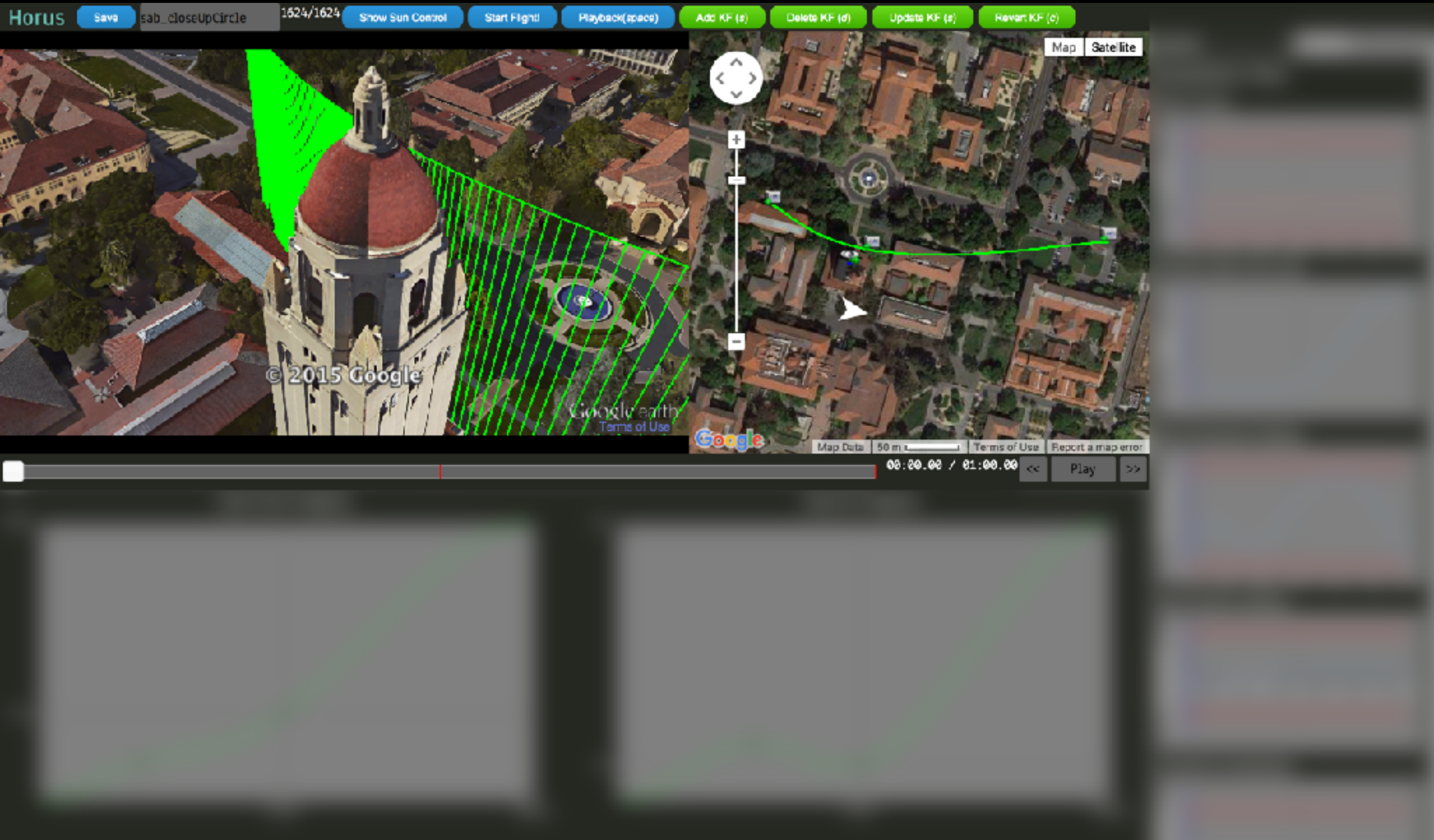
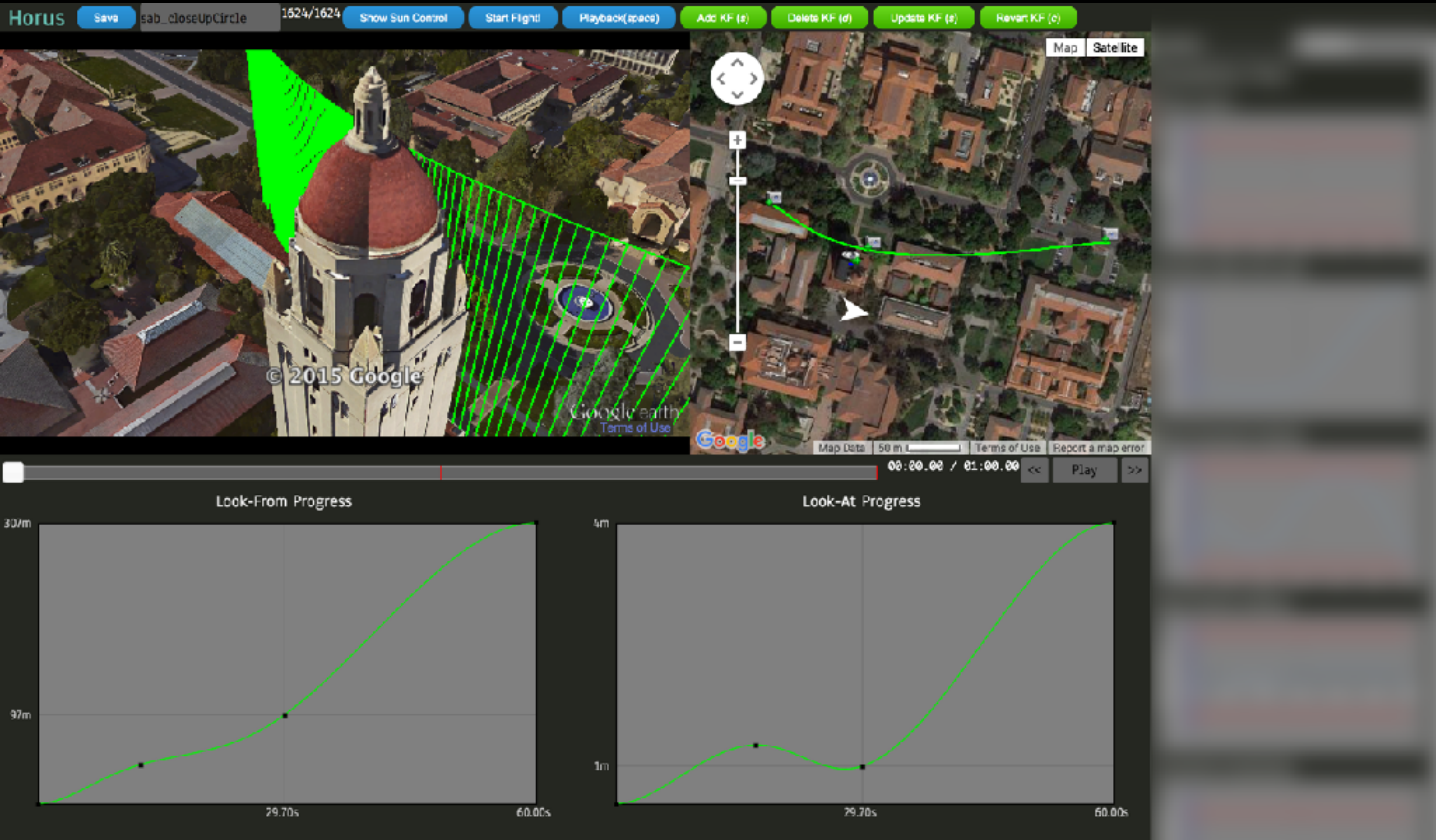
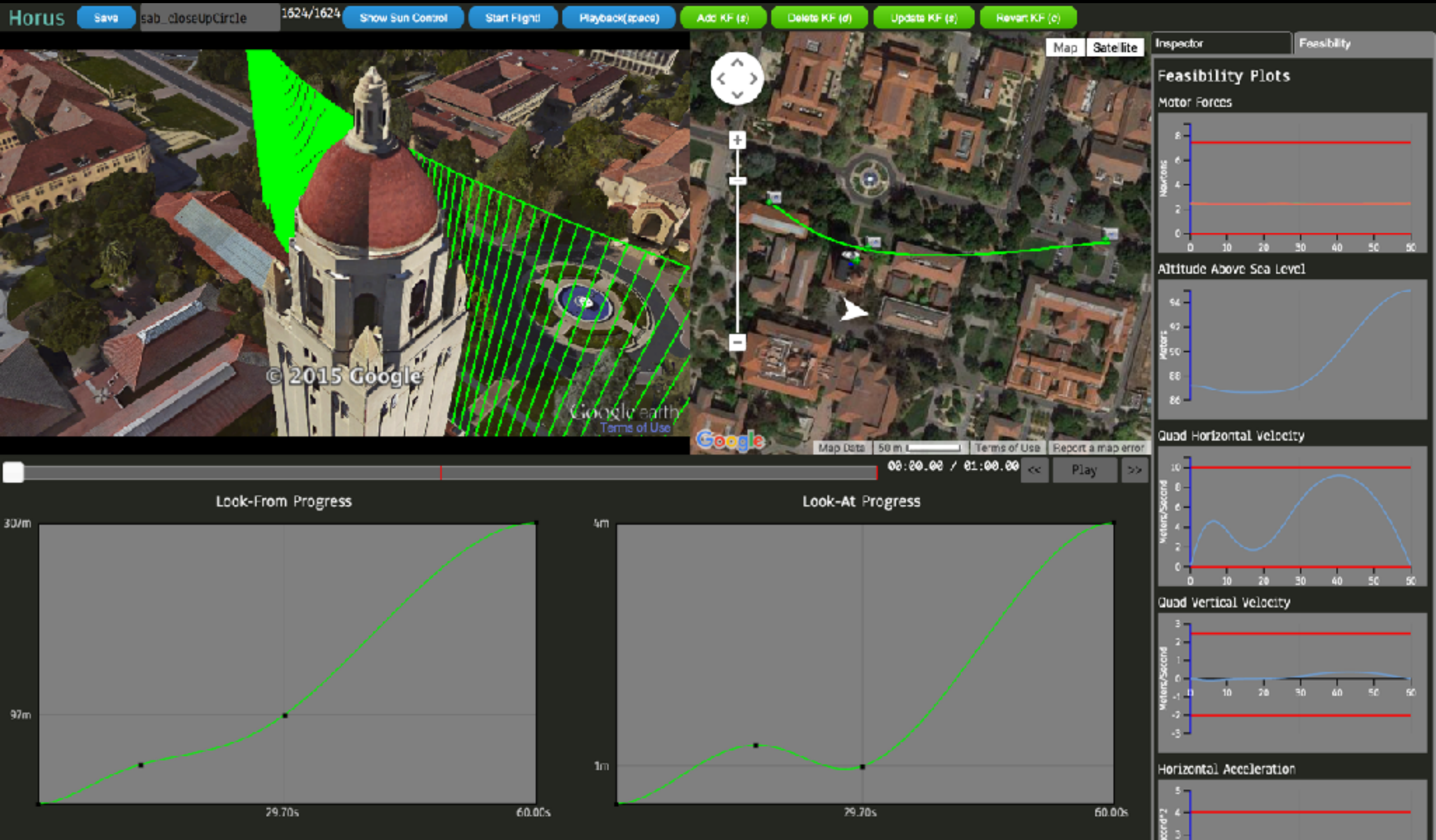


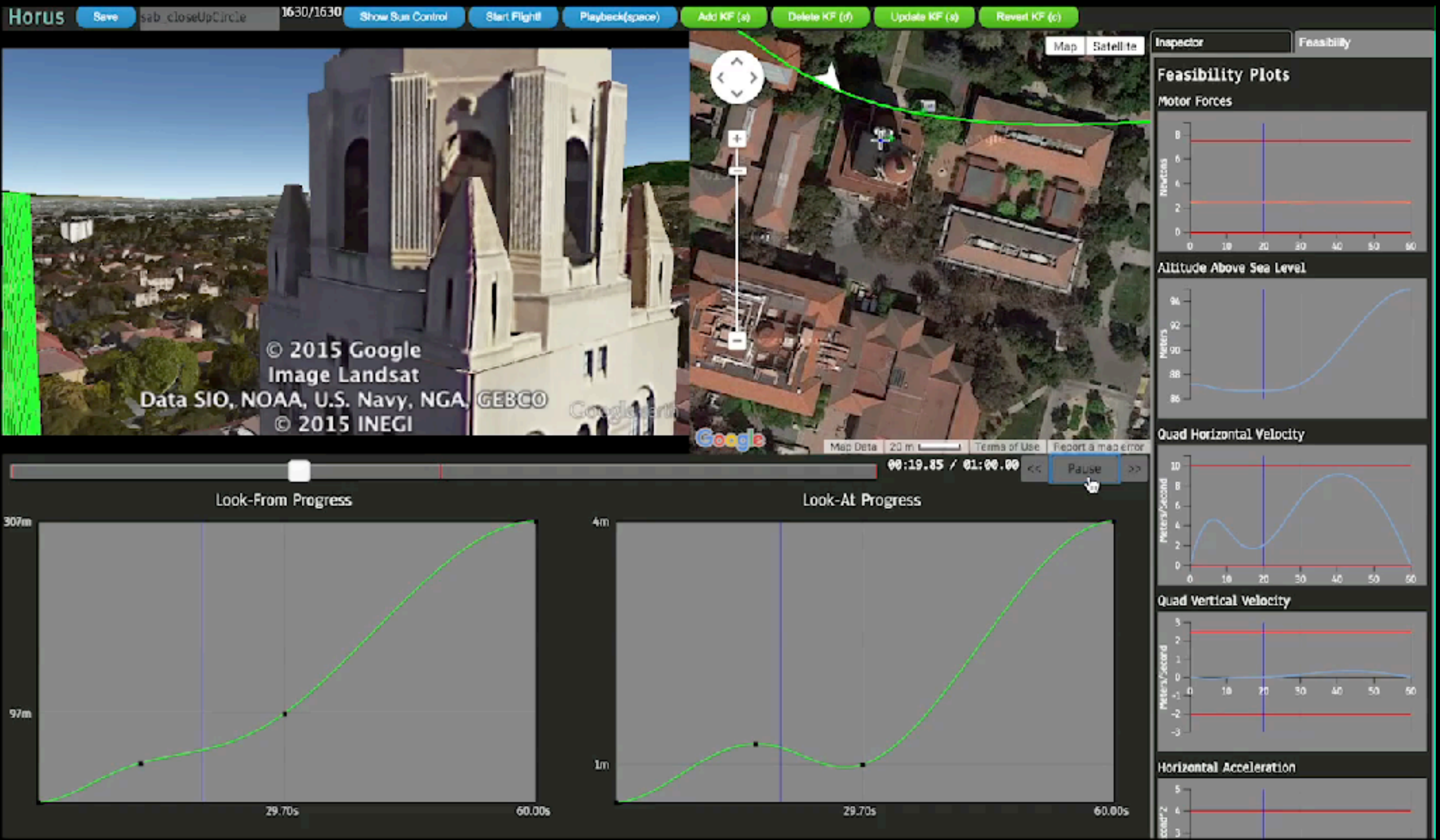
PRECISELY CONTROL TIMING WITH PROGRESS CURVES



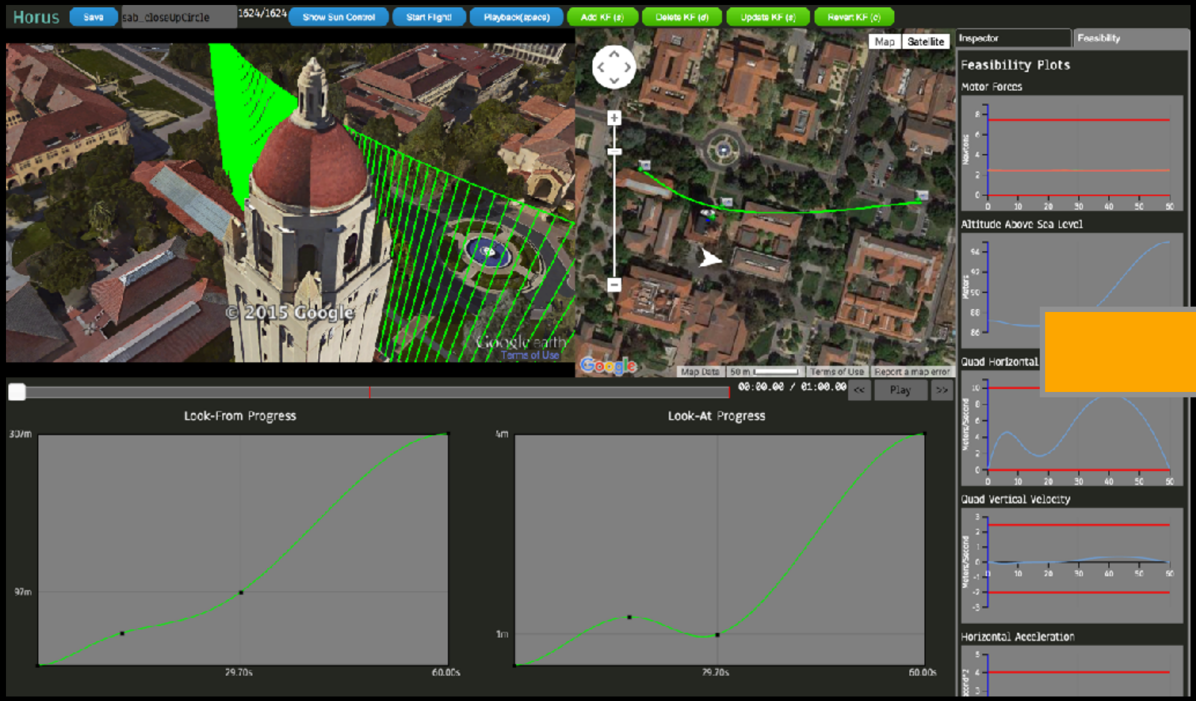
VISUAL FEEDBACK REGARDING QUADROTOR BEHAVIOR



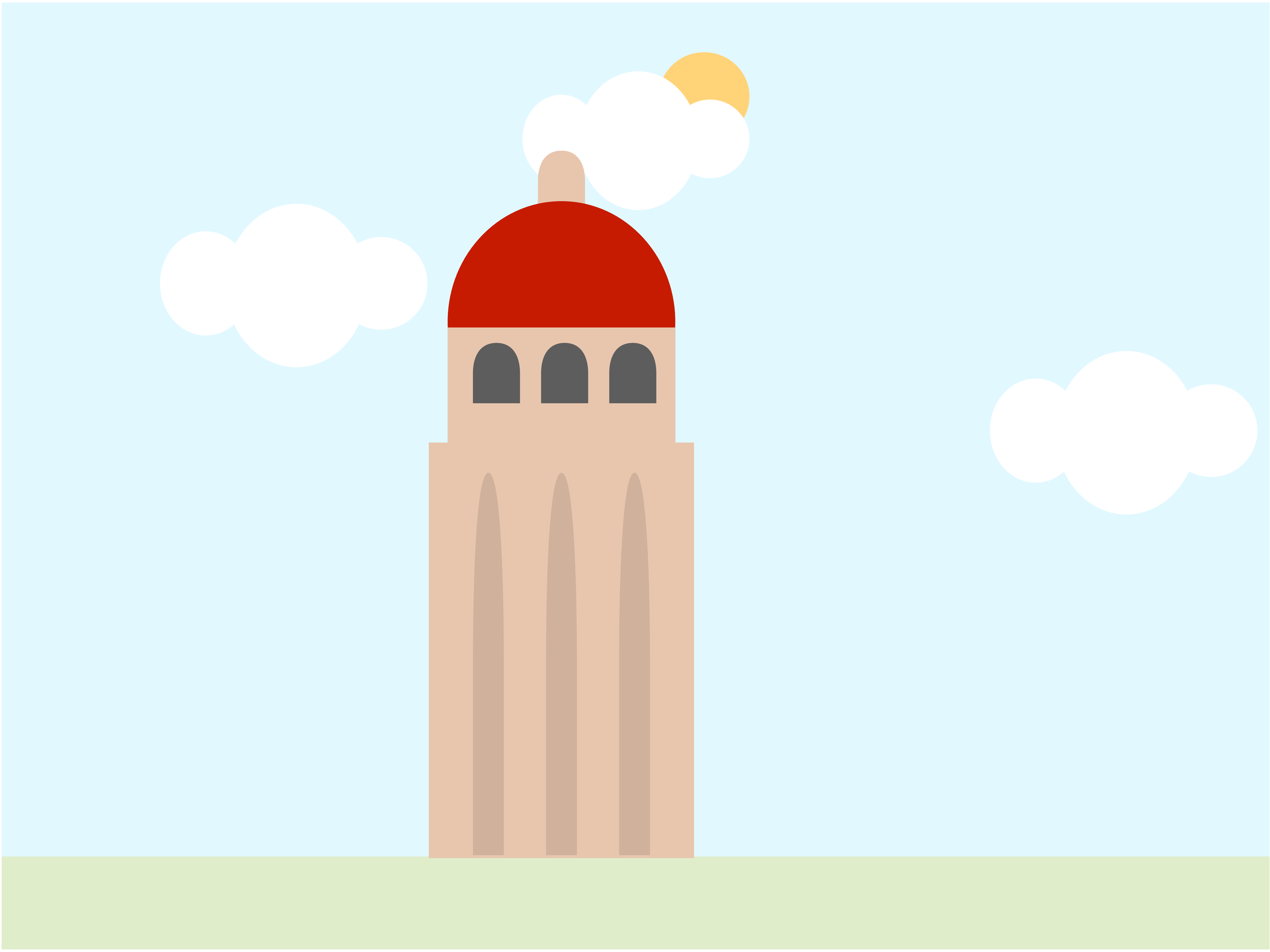
PREVIEW SHOT BEFORE FLIGHT

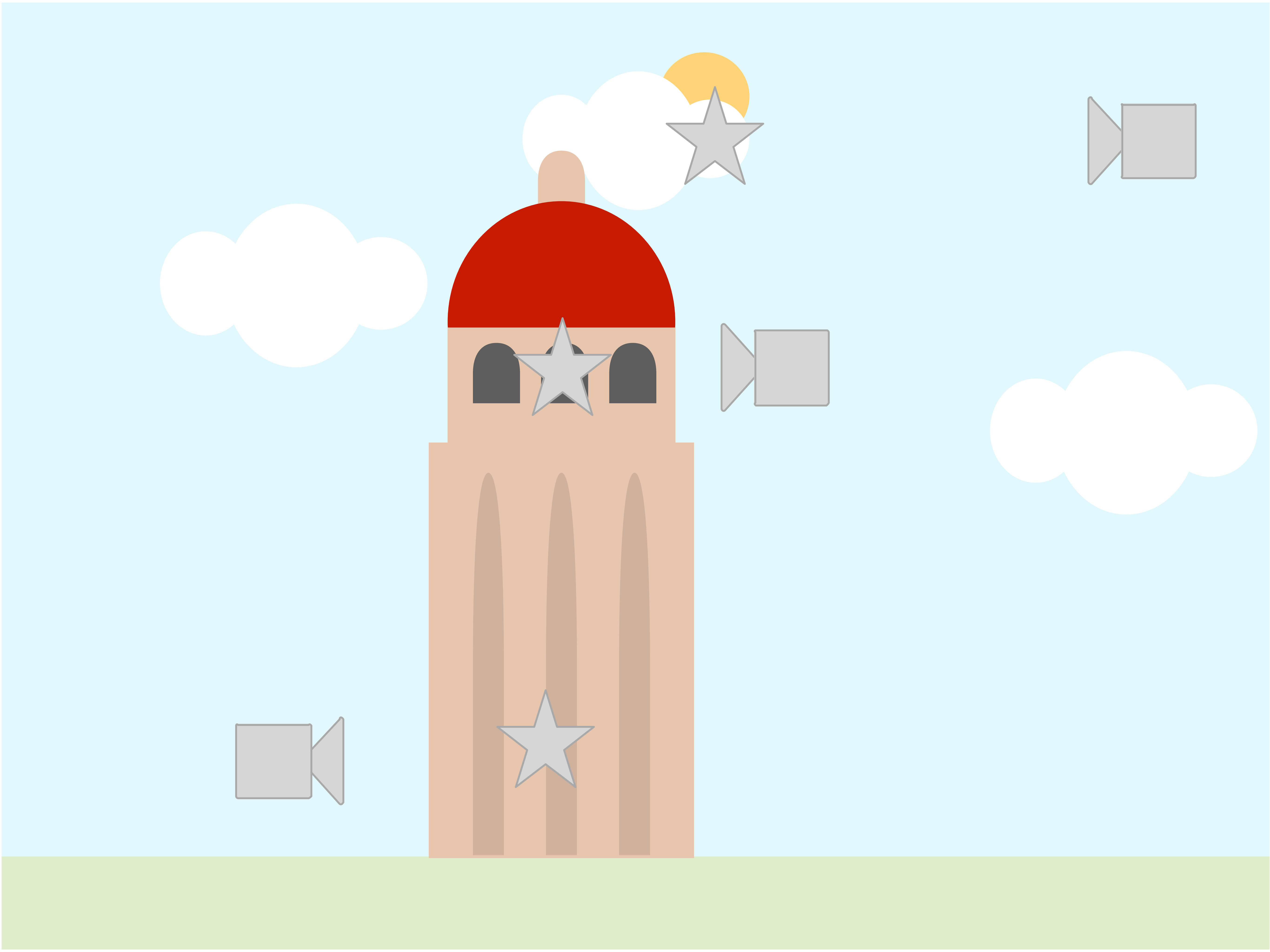


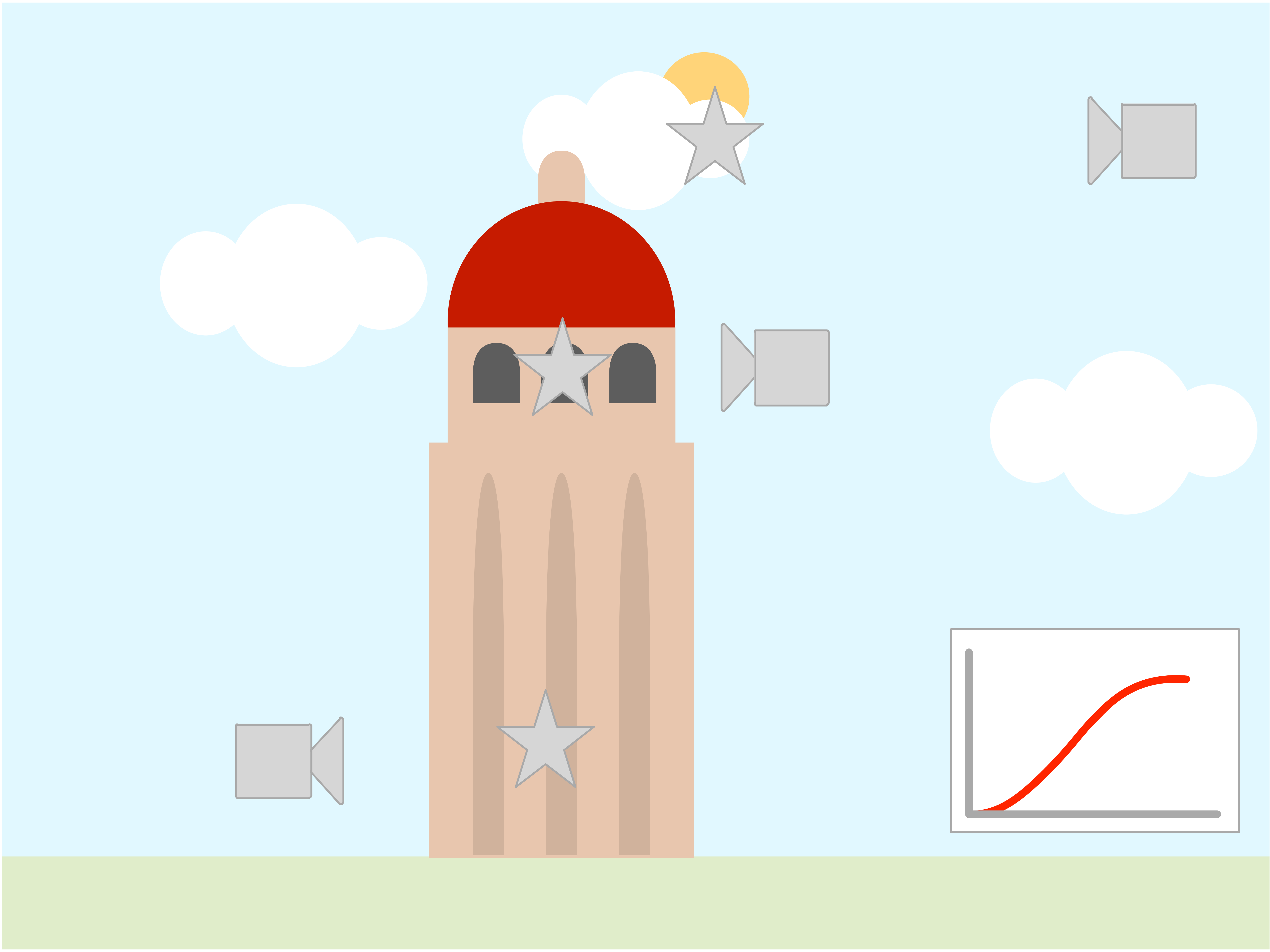
ONE-CLICK AUTONOMOUS CAPTURE

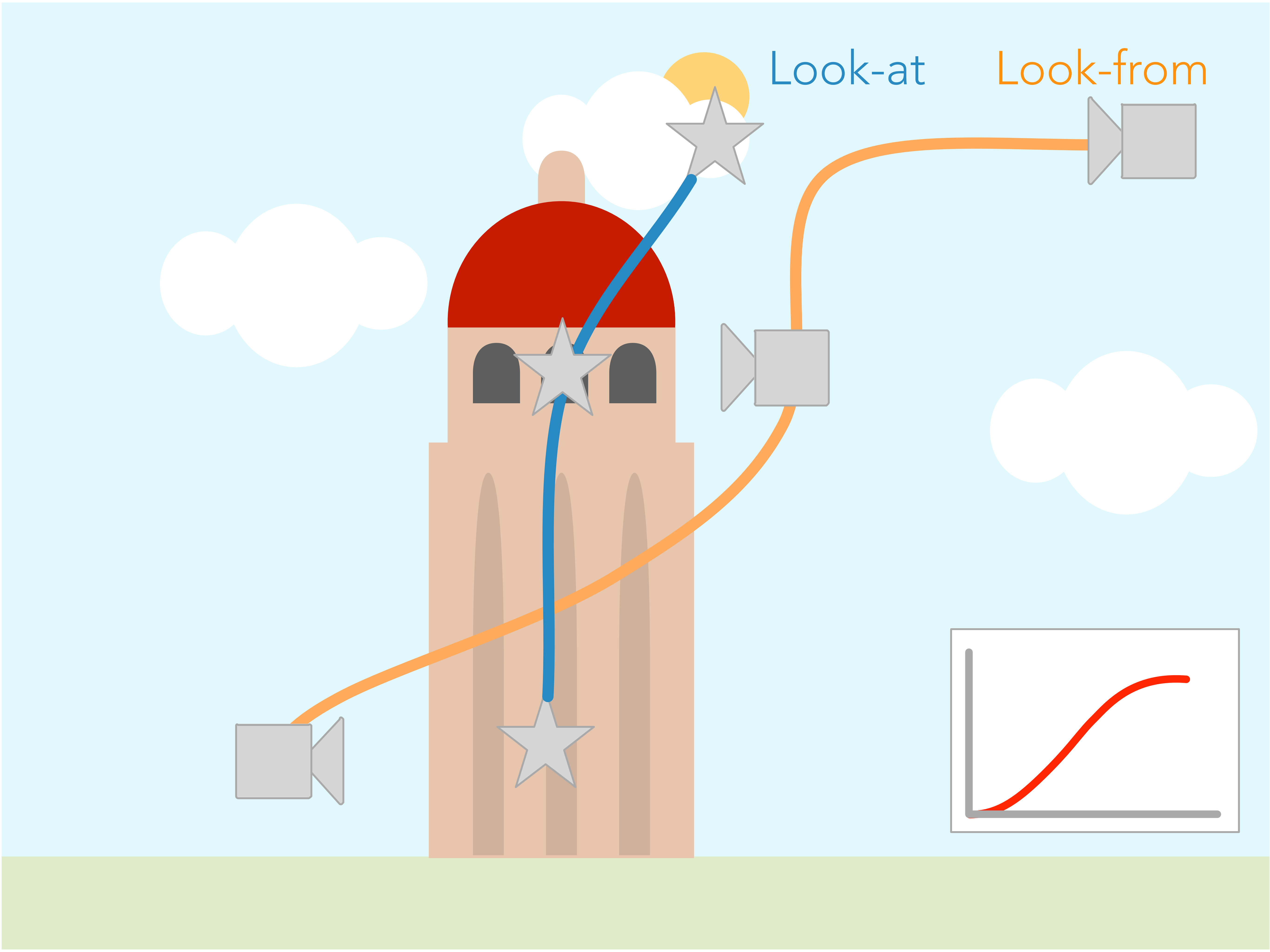


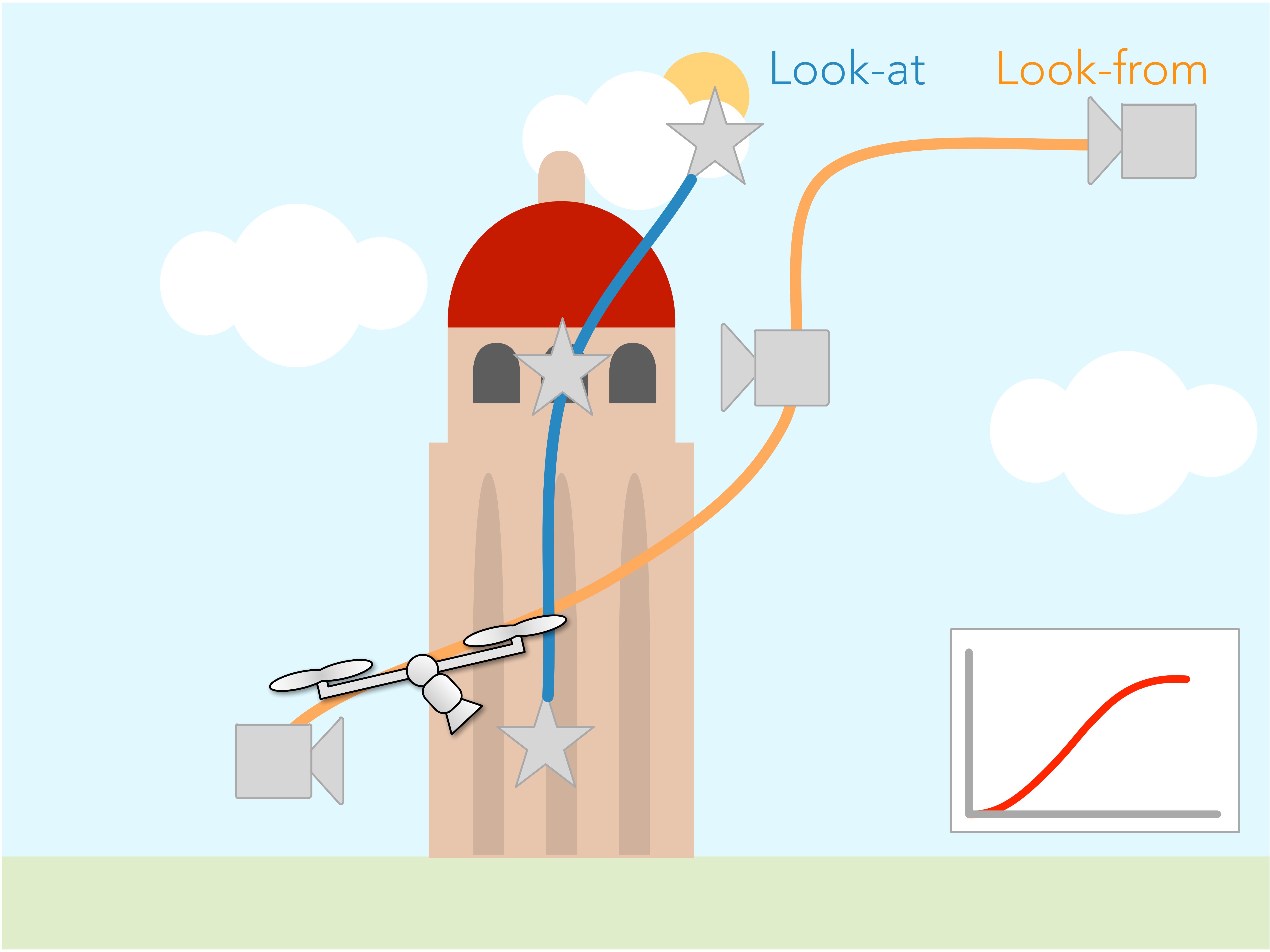
TECHNICAL APPROACH



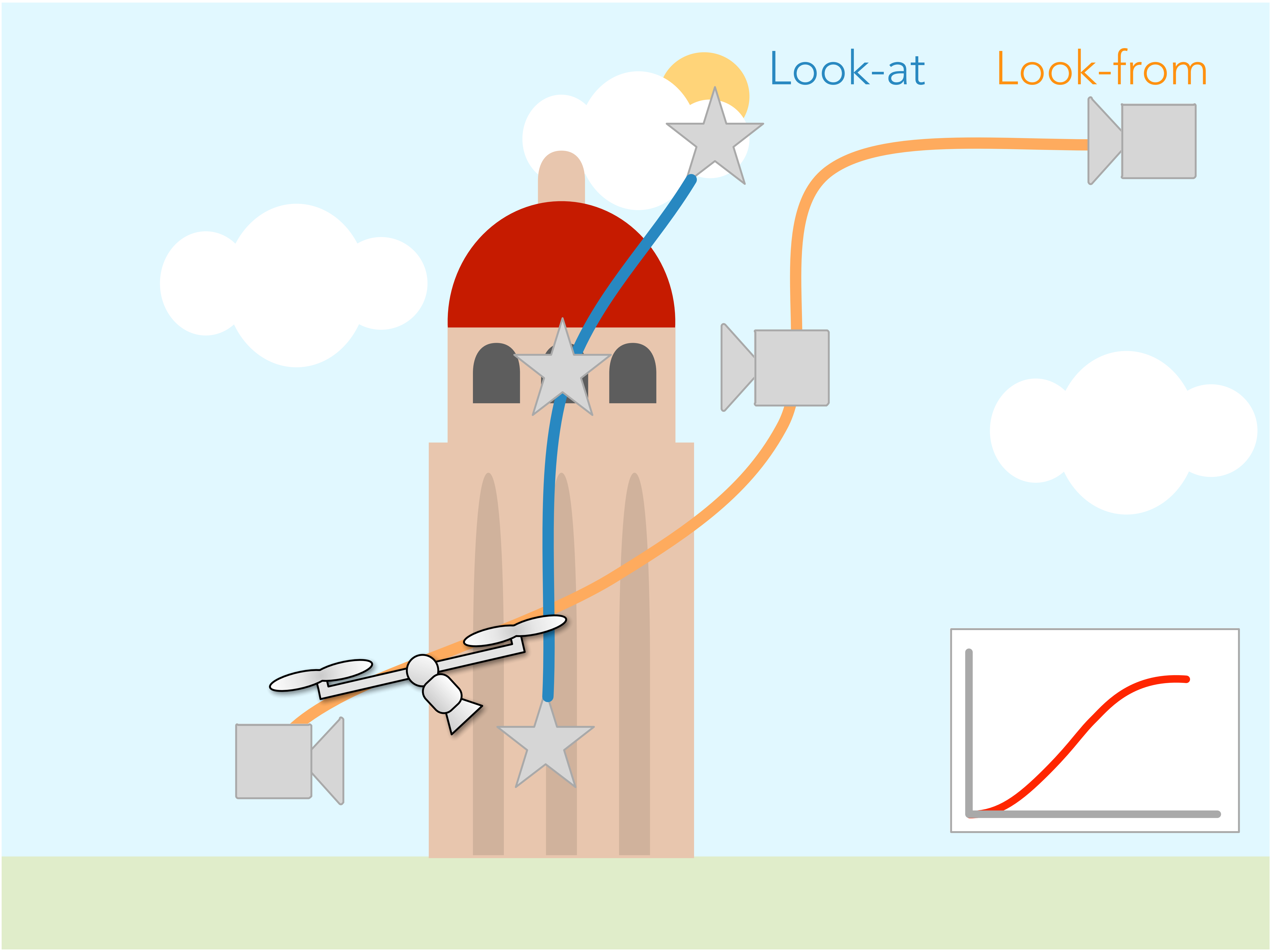




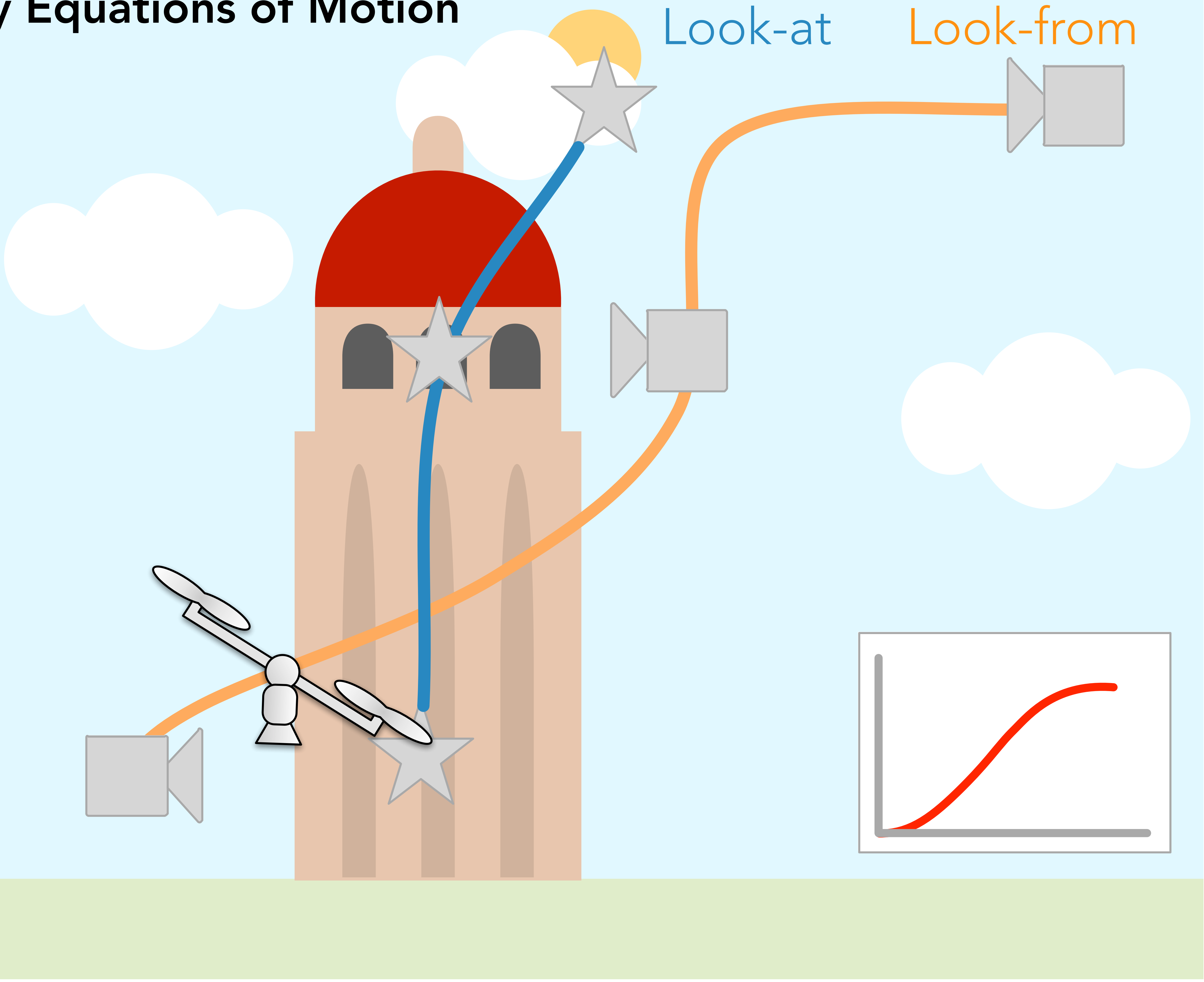

Look-at
Look-from



Look-at
Look-from

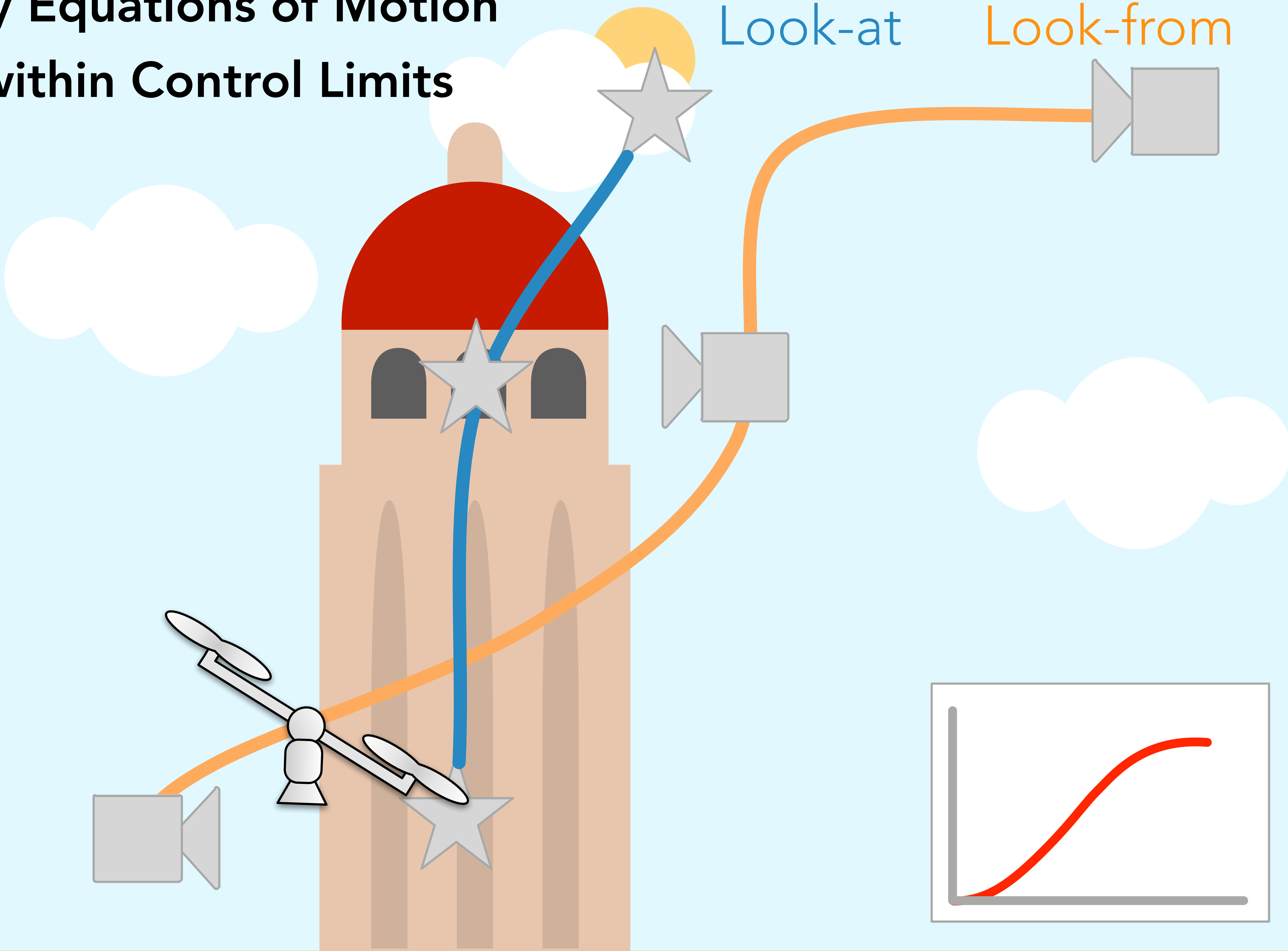

Look-at
Look-from

Satisfy Equations of Motion



Satisfy Equations of Motion

Stay within Control Limits



Physically Feasible

CHALLENGE: HOW CAN WE FIND PHYSICALLY FEASIBLE TRAJECTORIES?

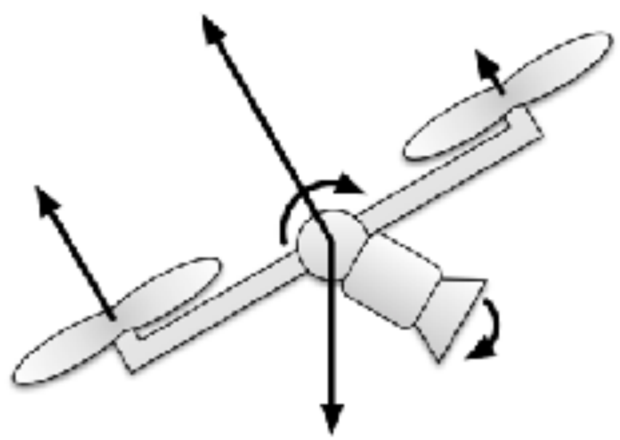
It’s known that as long as the 4th derivate of a trajectory exits, then it **satisfies quadrotor equations of motion**.

[Mellinger et al, 2013]

How do we add a **camera** to this?

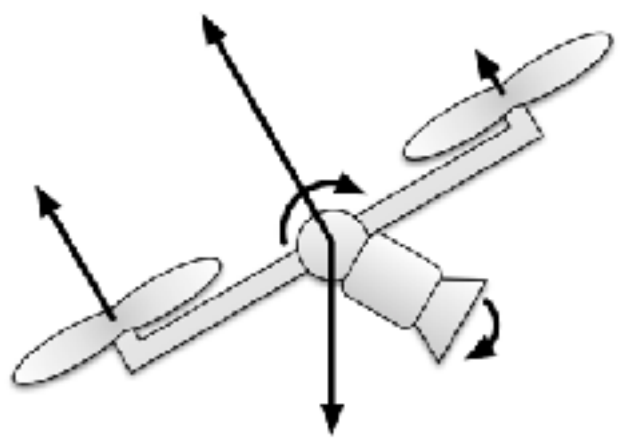
If we give users **timing control**,
how do we handle control limit violations?

ADDING A CAMERA TO A QUADROTOR



Physical model

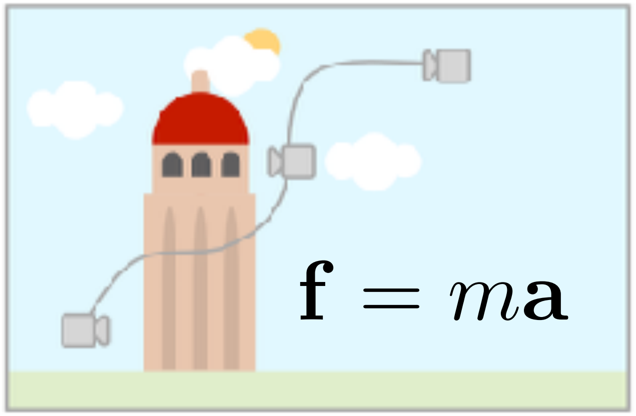
ADDING A CAMERA TO A QUADROTOR



Physical model

Look-from and Look-at trajectory must both be C4 continuous.

GENERATING TRAJECTORIES FOR OUR QUADROTOR CAMERA



Generate trajectories that satisfy equations of motion

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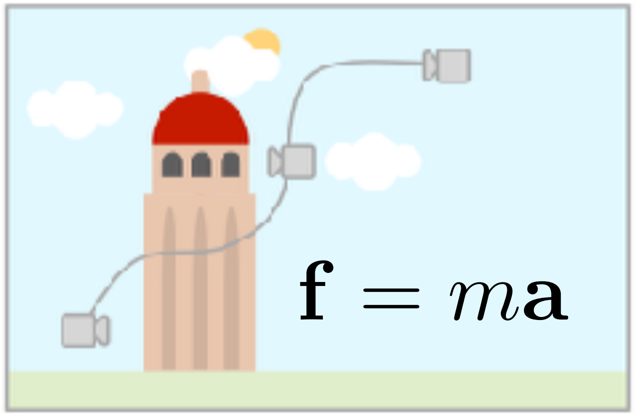
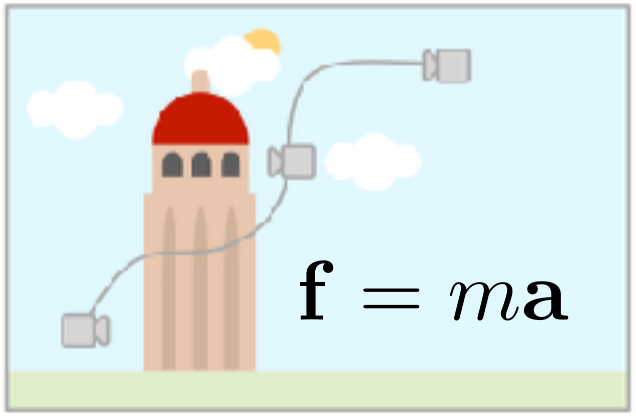


Generate trajectories that satisfy equations of motion

Interpolate using C4 continuous polynomial splines

Optimize for smoothness using a convex quadratic program

GENERATING TRAJECTORIES FOR OUR QUADROTOR CAMERA

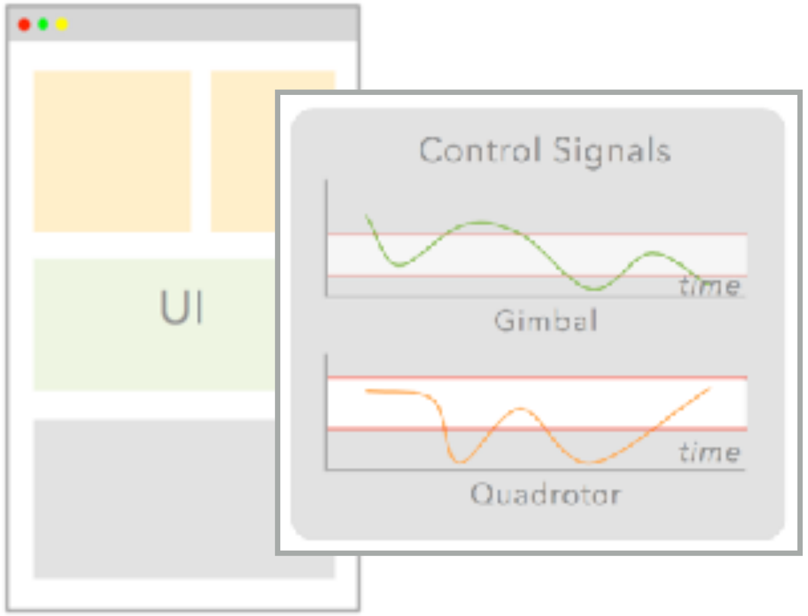


Generate trajectories that satisfy equations of motion **but not necessarily the control limits**

Interpolate using C4 continuous polynomial splines

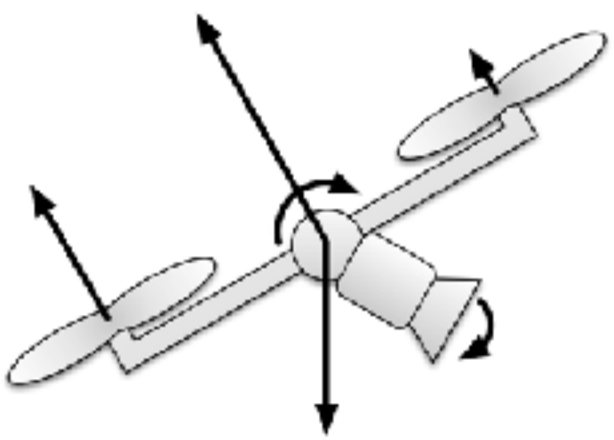
Optimize for smoothness using a convex quadratic program

DEALING WITH CONTROL LIMITS

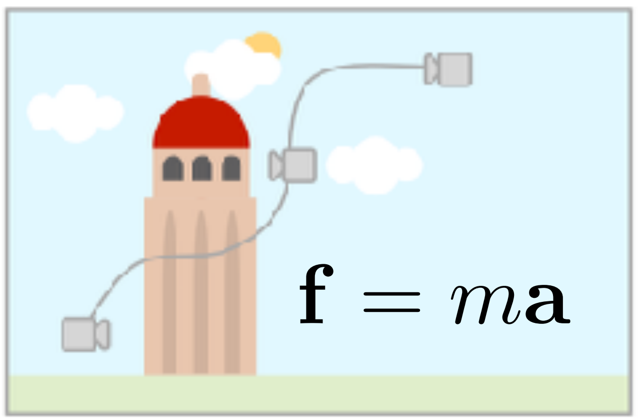


Display control forces in UI,
require user to stay within
control limits

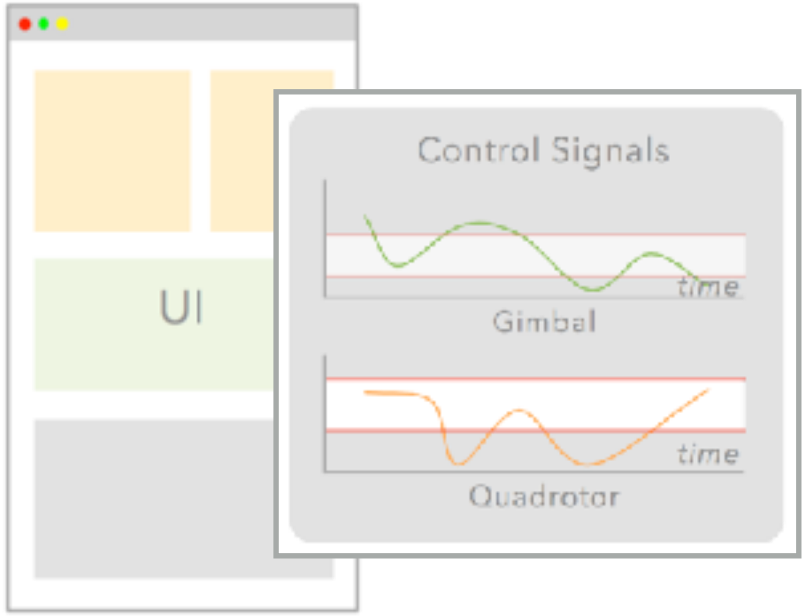
TECHNICAL APPROACH FOR GENERATING FEASIBLE TRAJECTORIES



Physical model proves C4 continuity requirement holds for Quadrotor Cameras



Generate trajectories that satisfy equations of motion but not necessarily control limits



Display control forces in UI, require user to stay within control limits

IMPLICATION: EXPRESSIVENESS

We can express
any trajectory a quadrotor camera can execute

EVALUATION OF OUR TOOL

USER STUDY PROTOCOL

Four participants: **two novice** cinematographers, **two expert** cinematographers with quadrotor experience

90 minutes to create two feasible shots: one instructed, one open-ended

Autonomously capture shots on location

After capture, experts identified shot components that would make for challenging manual capture

KEY QUESTIONS

How effective was our **visual preview?**

How did subjects use **feasibility feedback**?

Did we **enable cinematographers** to capture challenging shots?

VISUAL PREVIEW MATCHES FRAMING AND COMPOSITION OF CAPTURED SHOT

Expert 2, Freeform Shot

BUT LIMITED BY 3D MODEL AND QUADROTOR SENSOR ACCURACY

Novice 2, Freeform Shot

USERS CREATED FEASIBLE PATHS IN UNEXPECTED WAYS

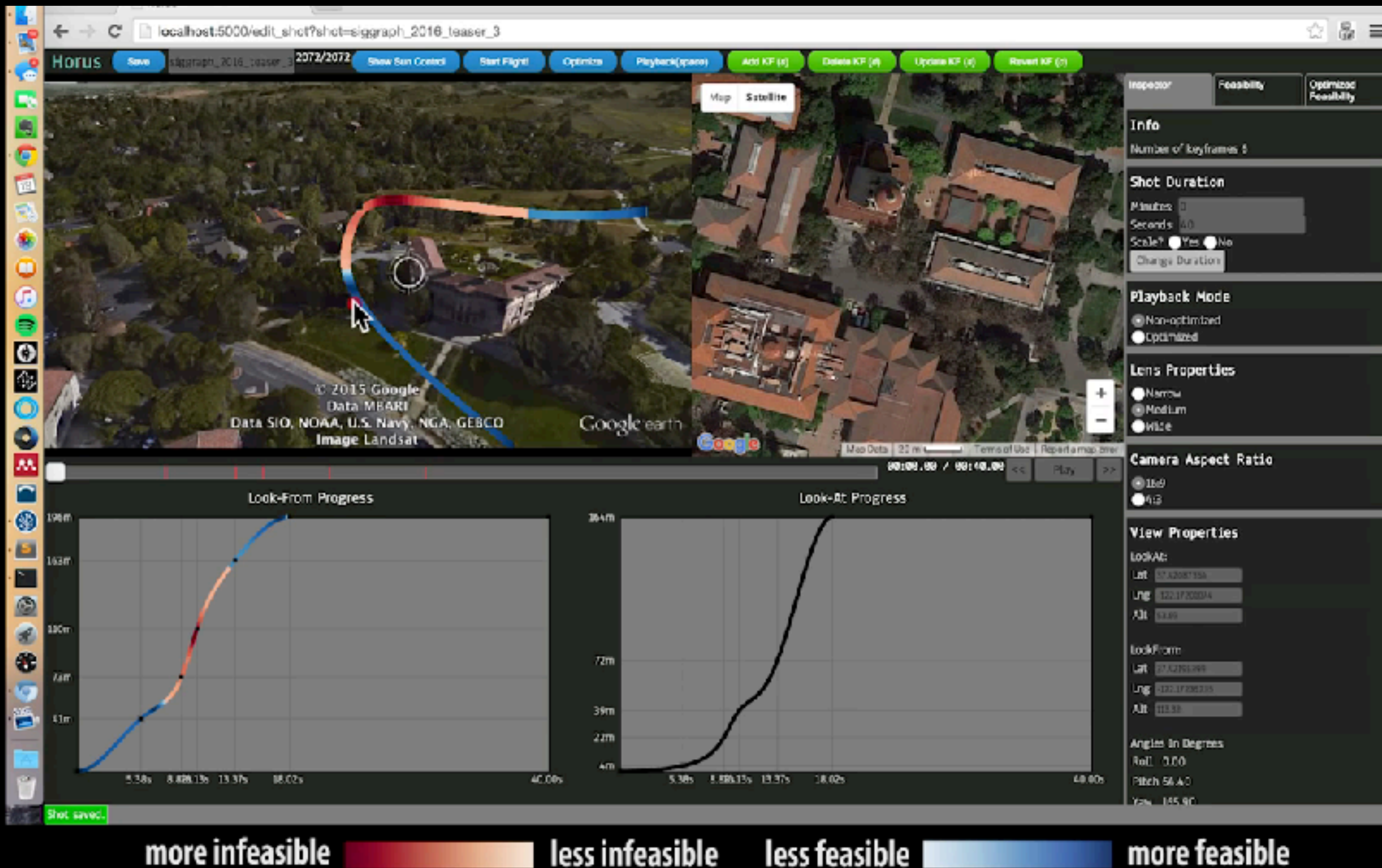
VISUAL FEASIBILITY FEEDBACK

All users successfully ensured feasibility

Complex behavior from feasibility feedback:

- Stretch the time
- Tweak trajectory
- Create completely different shot

ROBERTS AND HANRAHAN EXTENDED HORUS WITH AUTOMATED SMART TIME STRETCHING



[Roberts and Hanrahan SIGGRAPH 2016]

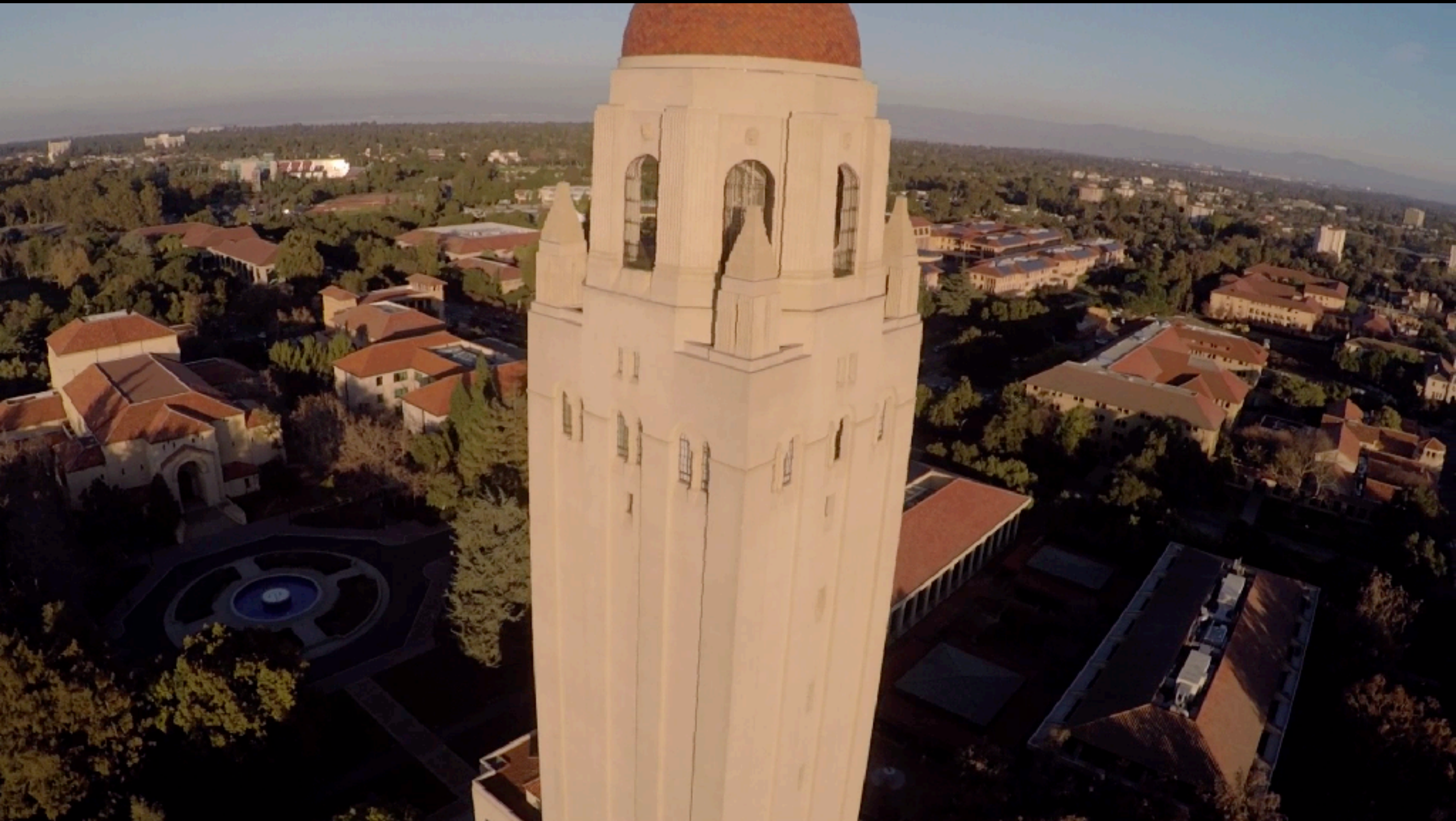
WE ENABLED NOVICE AND EXPERT CINEMATOGRAPHERS TO CAPTURE CHALLENGING SHOTS

REGARDLESS OF SKILL LEVEL, USERS CREATE CHALLENGING SHOTS

Expert 1, Instructed Shot

REGARDLESS OF SKILL LEVEL, USERS CREATE CHALLENGING SHOTS

Novice 2, Instructed Shot



REGARDLESS OF SKILL LEVEL, USERS CREATE CHALLENGING SHOTS

1.5X
Expert 1, Freeform Shot

1x
Novice 2, Freeform Shot


10X

SUMMARY

Demonstrated a tool in which cinematographers could express high quality shots for quadrotor cameras, even if they were novices.

Showed how 3D Animation primitives and the look-at look-from camera model can be used to fly quadrotor cameras.

WITH HORUS, THE USER ACTS AS A
CINEMATOGRAPHER

COMPOSING SHOTS
USING KEYFRAMES AND EASING CURVES

PROBLEM

QUADROTOR CINEMATOGRAPHY REQUIRES

TECHNICAL SKILL OF FLYING, AND ARTISTIC SKILL OF COMPOSITION, SIMULTANEOUSLY APPLIED IN REAL TIME

PROBLEM

QUADROTOR CINEMATOGRAPHY REQUIRES

~~TECHNICAL SKILL OF FLYING~~, AND ARTISTIC SKILL OF COMPOSITION, ~~SIMULTANEOUSLY APPLIED IN REAL TIME~~

by **preplanning** camera movements

OVERVIEW

Compose shots using classic 3D Animation primitives, adapted to respect quadrotor camera physics [SIGASIA 2015]

Horus

A Tool for Shot Planning

Compose shots in real time using visual composition principles from filmmaking [arXiv 2016]

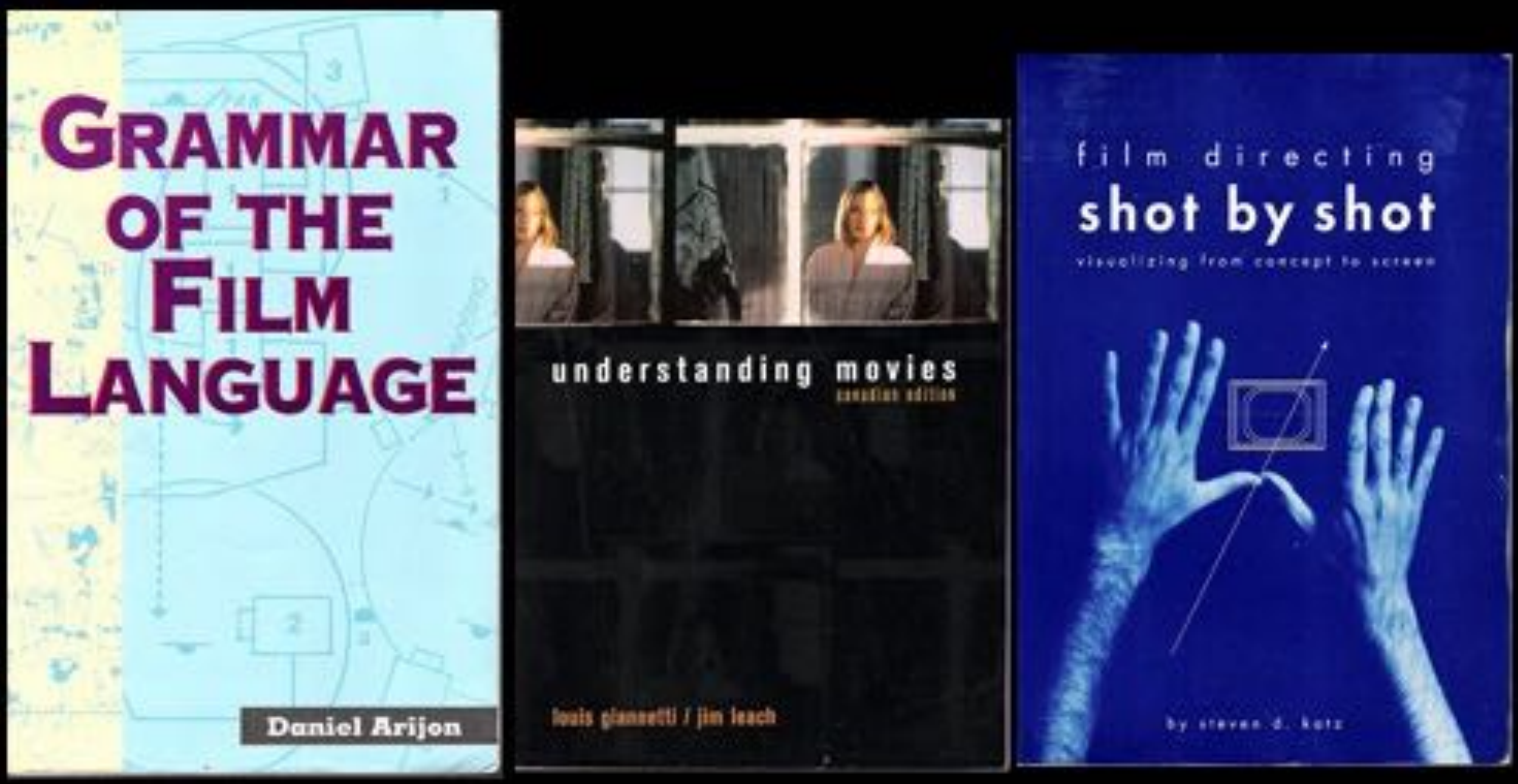
Drone Cinematographer

A Tool for Filming People

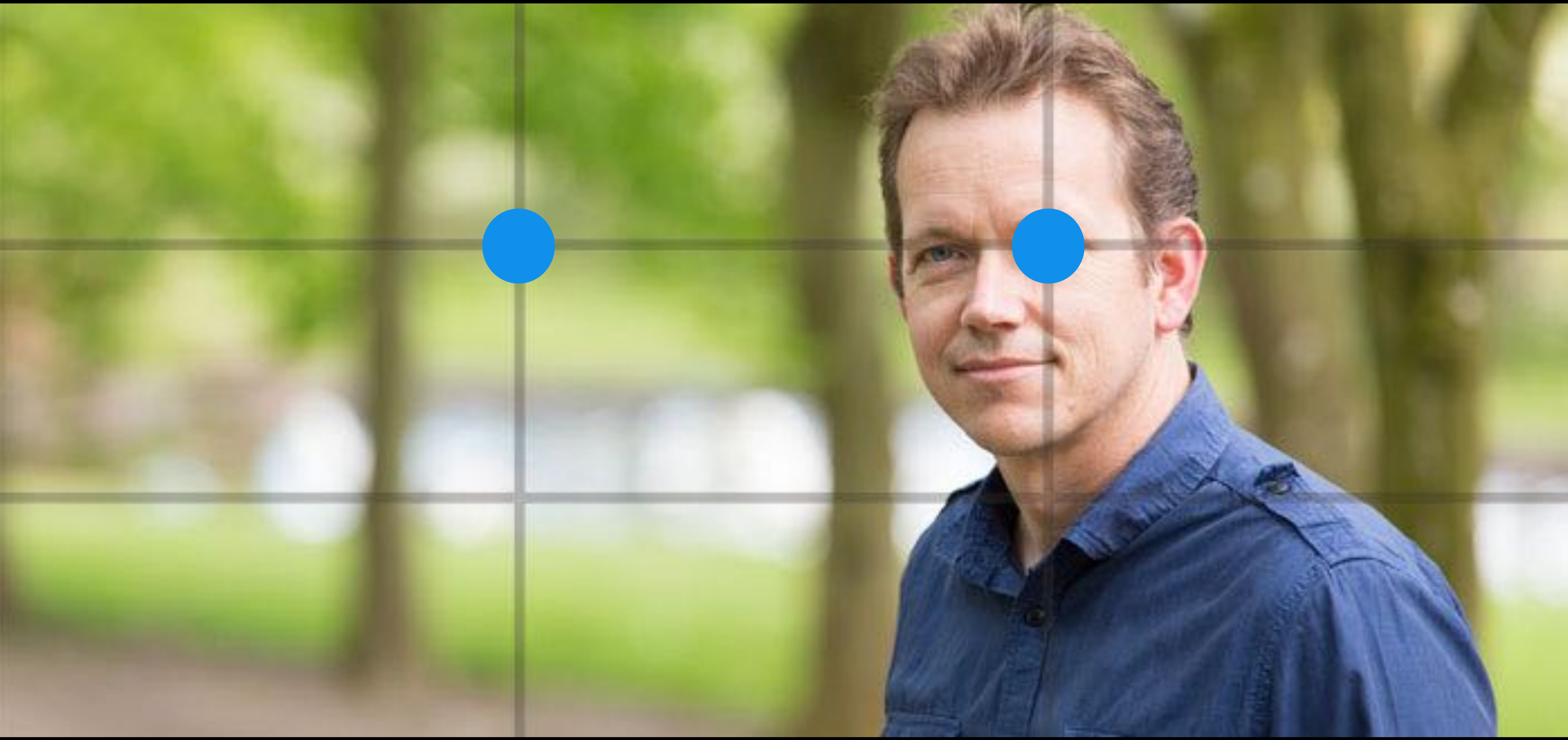
SHOT WITH DRONE CINEMATOGRAPHER

HOW MIGHT WE AUTOMATE THE COMPOSING OF SHOTS?

WHAT DO WE KNOW ABOUT VISUAL COMPOSITION? ABOUT SHOTS?



EXAMPLE OF VISUAL COMPOSITION PRINCIPLE: RULE OF THIRDS



[Ryan Bromley, 2016]

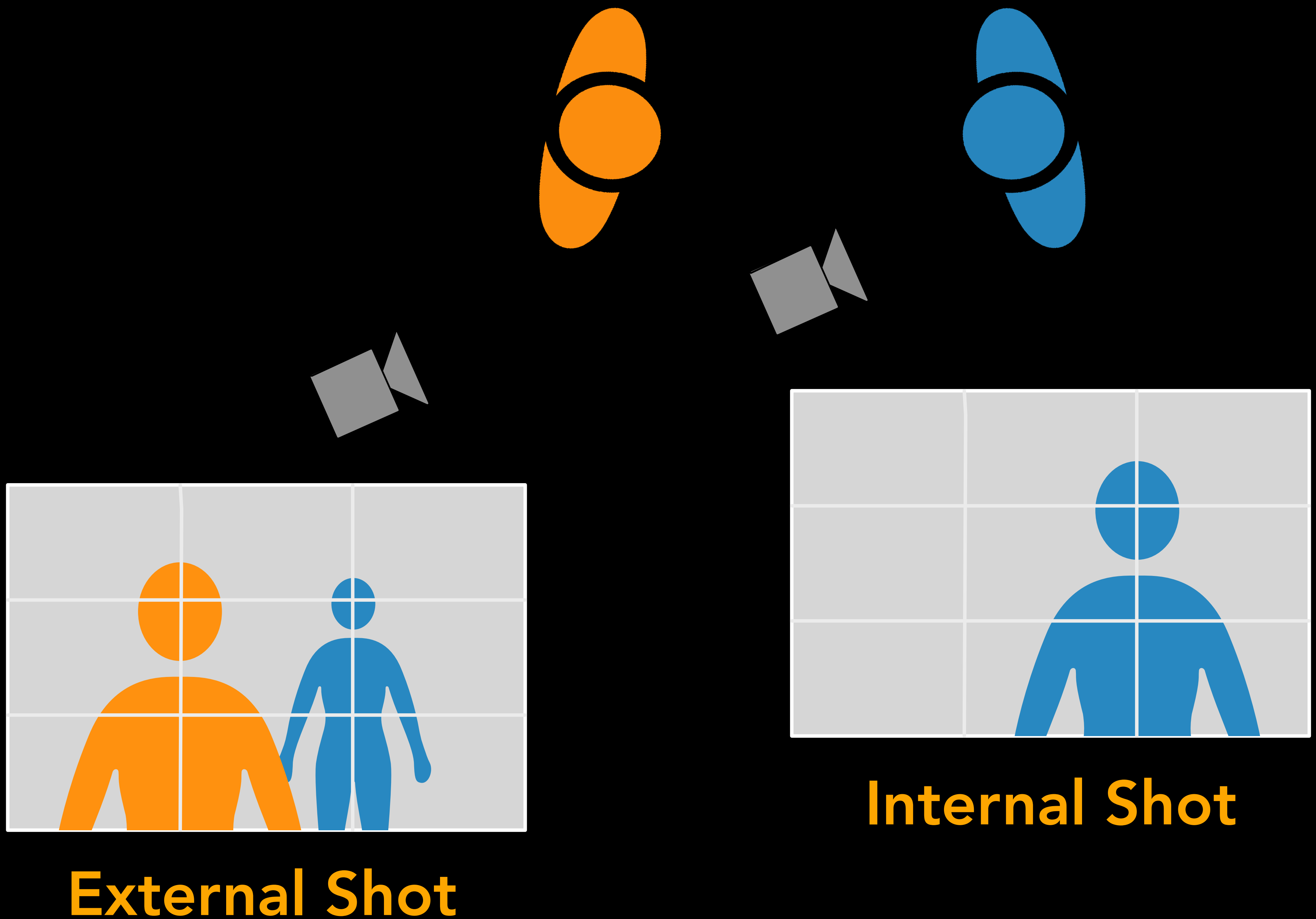
EXAMPLE OF VISUAL COMPOSITION PRINCIPLE: RULE OF THIRDS

[DesignShovel, 2016]

FILM LANGUAGE DESCRIBES CANONICAL SHOTS

[Arijon, 1976]

FILM LANGUAGE DESCRIBES CANONICAL SHOTS



[Arijon, 1976]

EXAMPLE OF VISUAL COMPOSITION PRINCIPLE: RESPECT LINE OF ACTION

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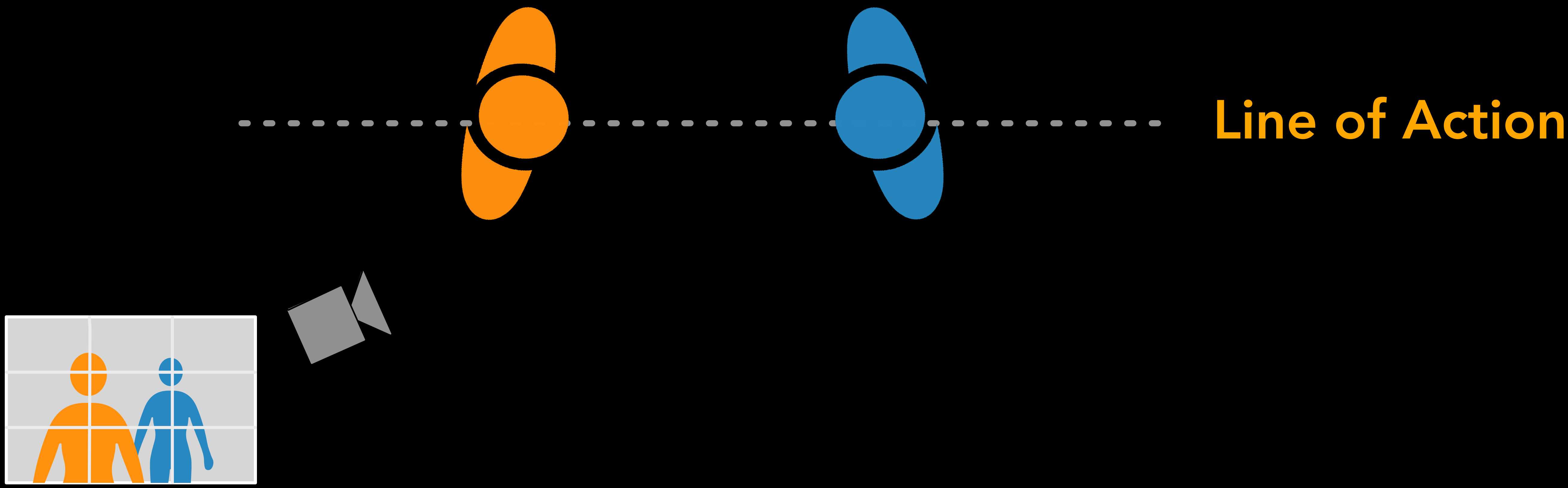

[Arijon, 1976]

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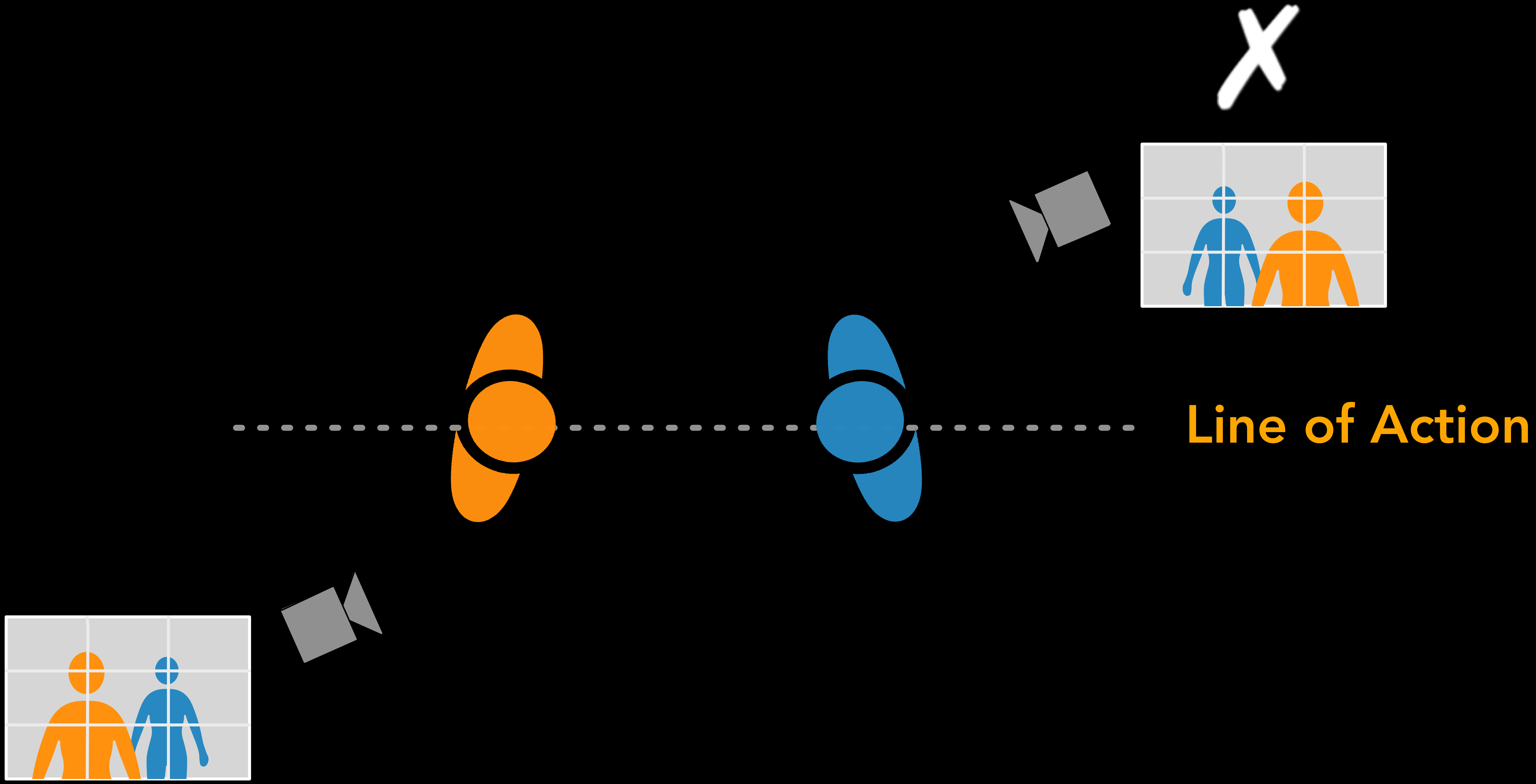

[Arijon, 1976]

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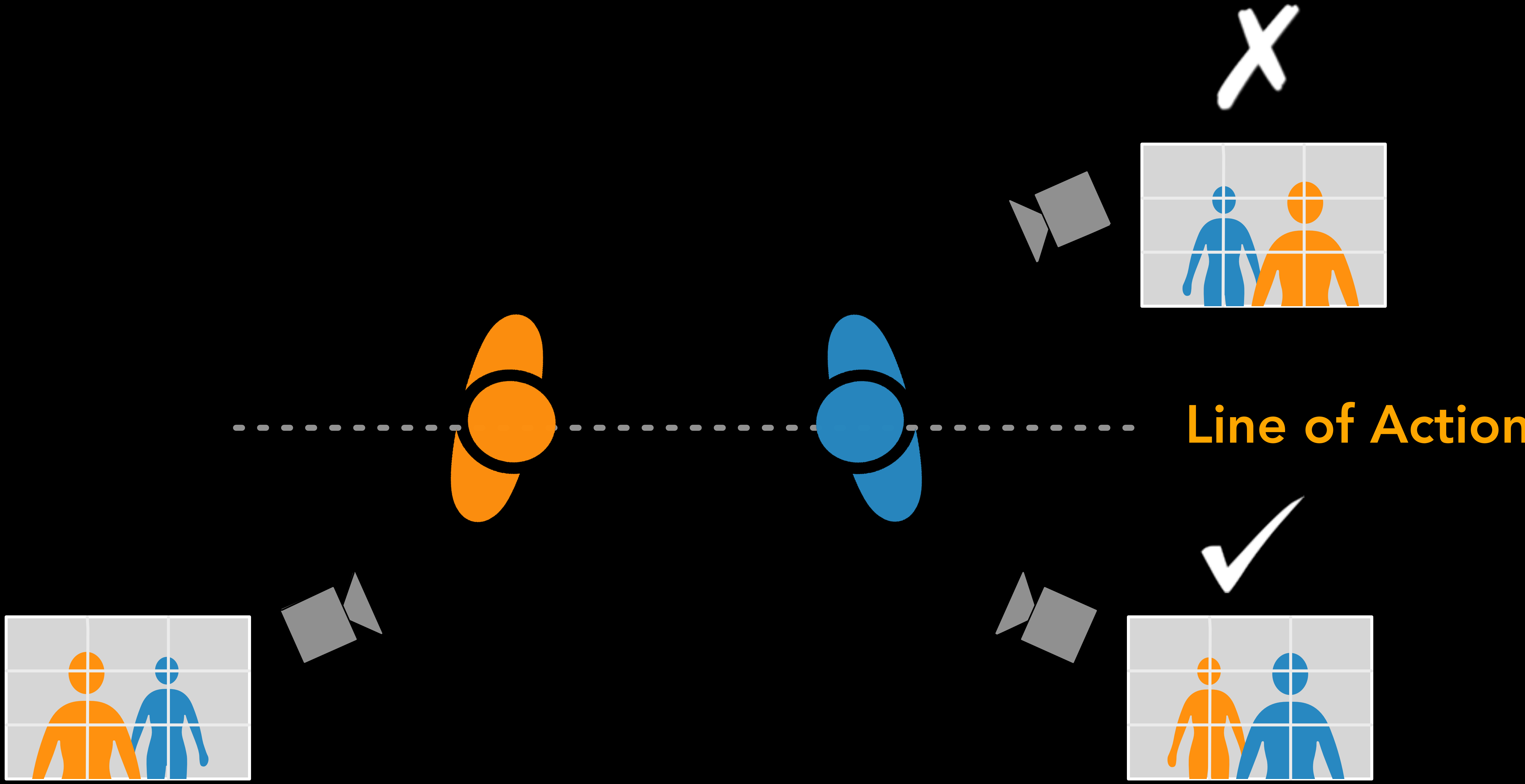
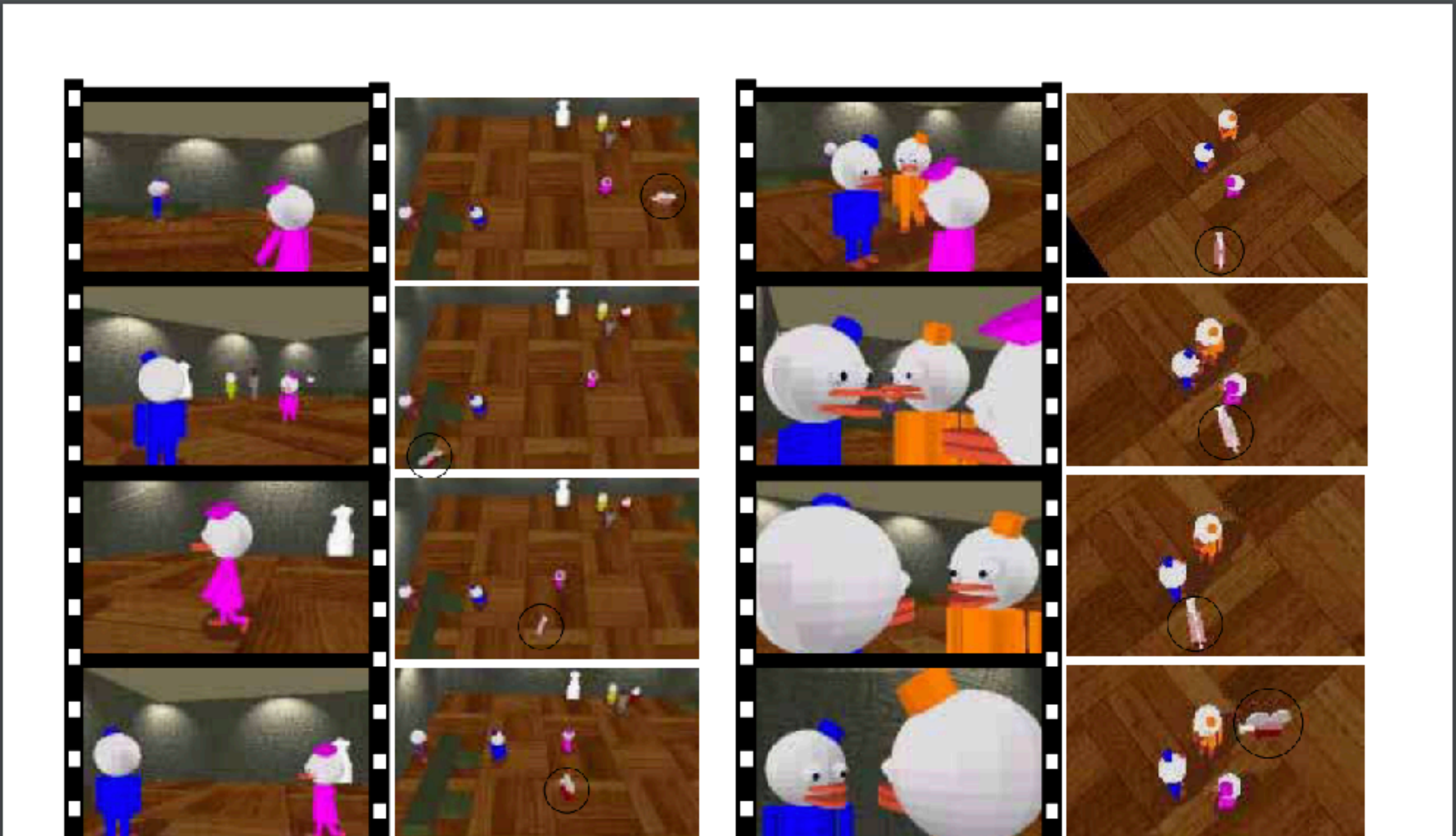


[Arijon, 1976]

THESE IDEAS HAVE BEEN USED IN COMPUTER GRAPHICS TO CONTROL CAMERAS

[He et al, 1999]



KEY IDEA

Use **canonical shots and composition principles** as control input to a Quadrotor Camera

Automate flying the quadrotor

Novices get **high quality visual composition**

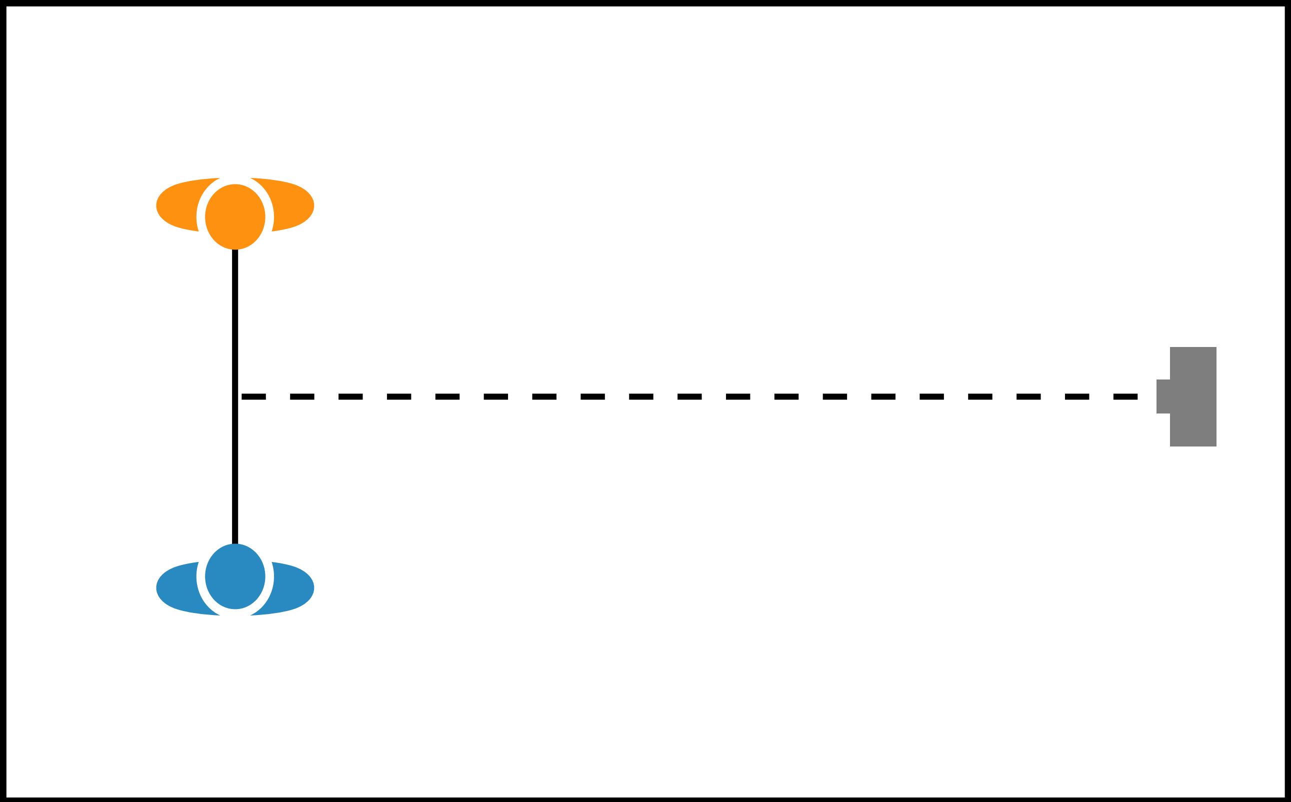
Can **react in real time**

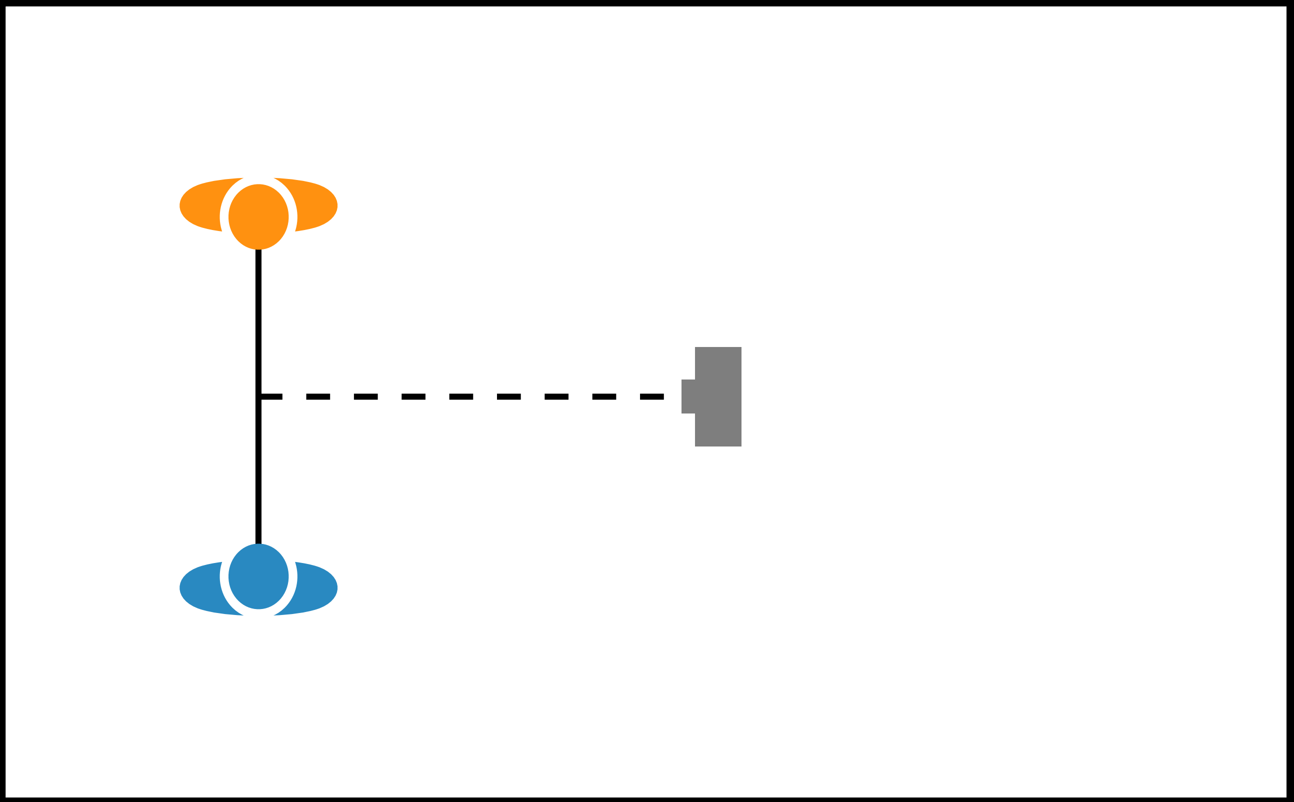
CANONICAL SHOTS

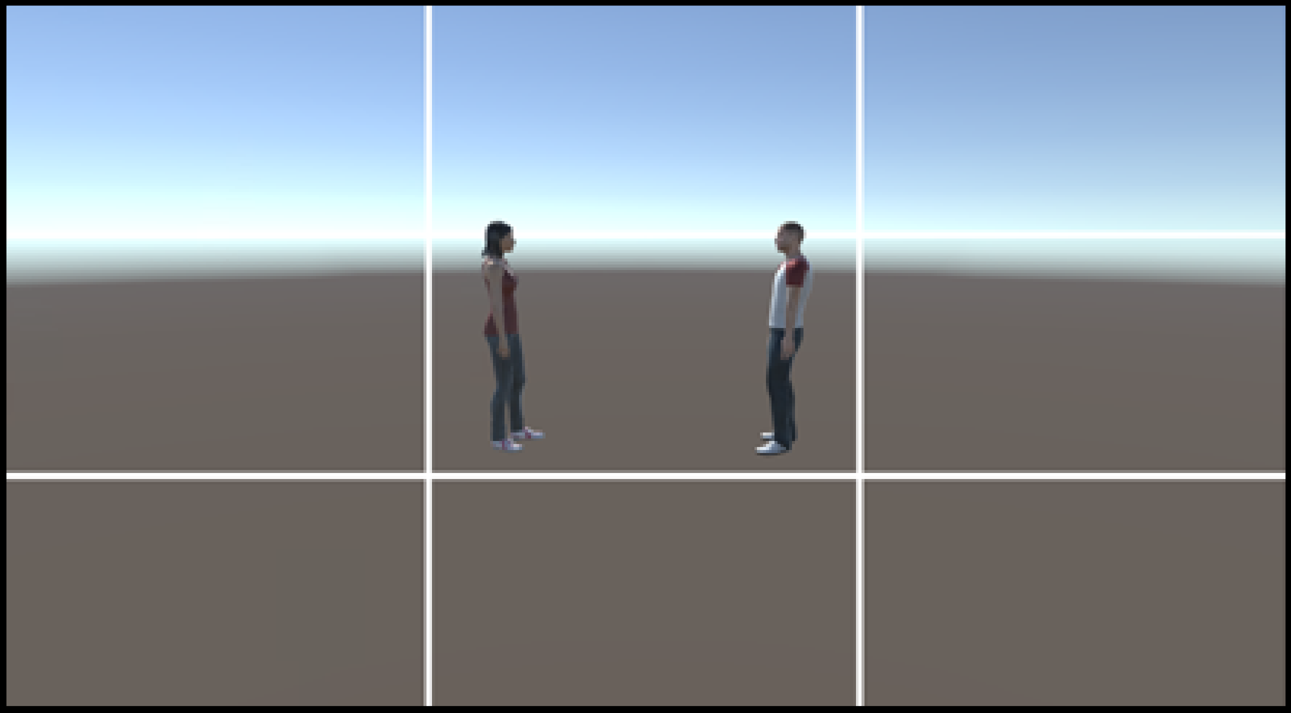
[He et al, 1999] [Rubin, 2002]

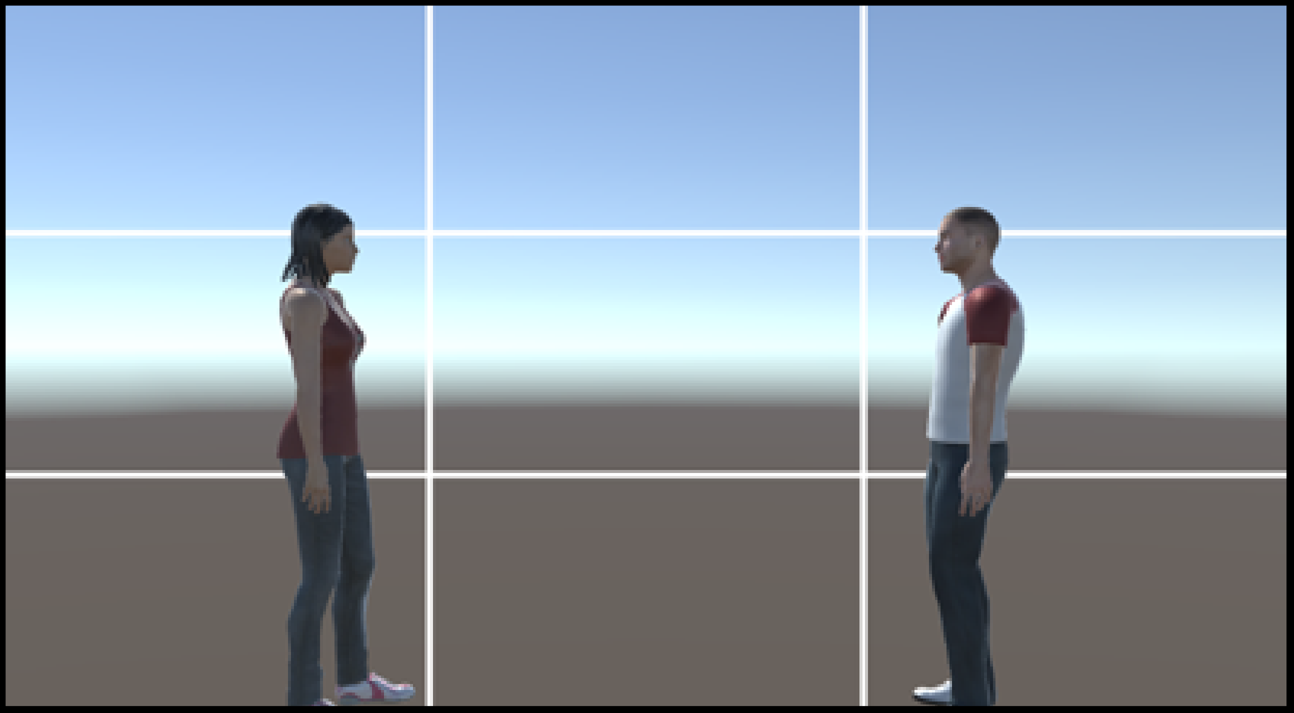
Apex

Close Apex









CANONICAL SHOTS

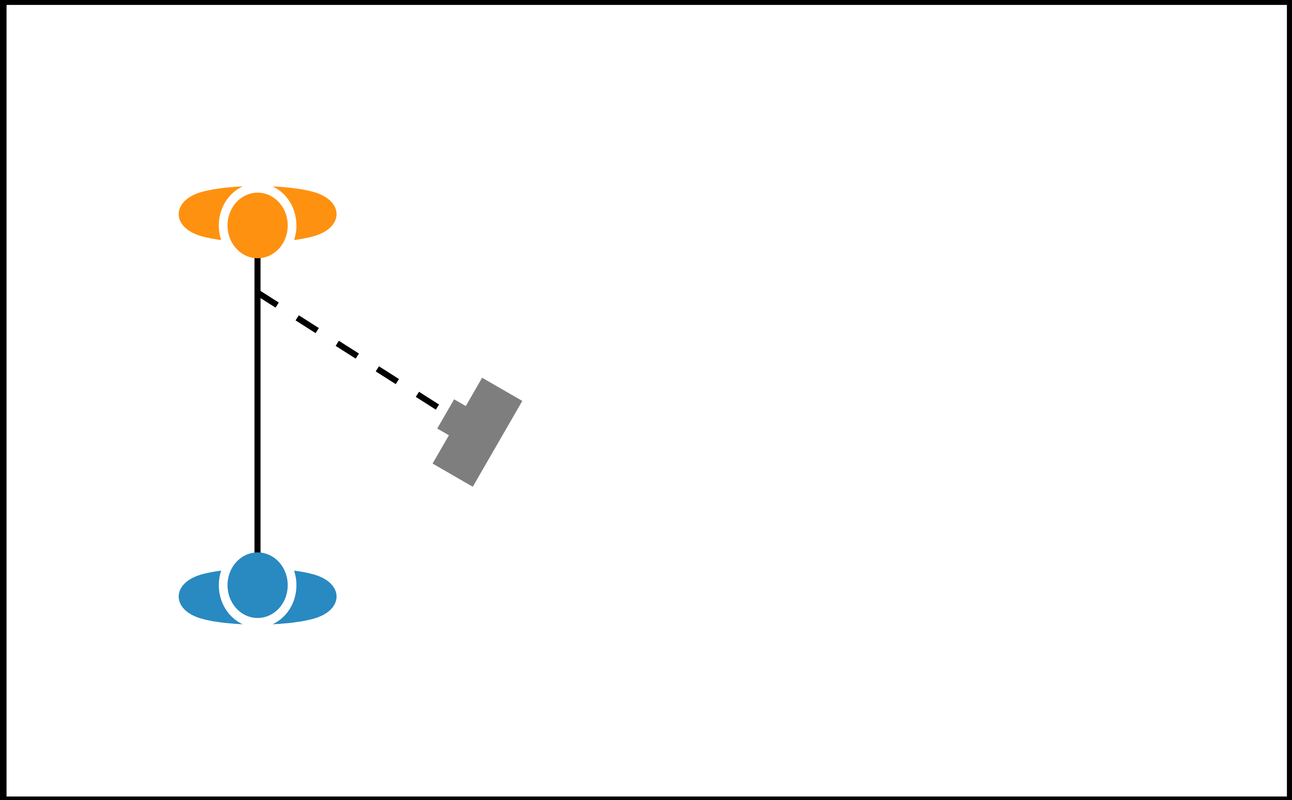
[He et al, 1999] [Rubin, 2002]

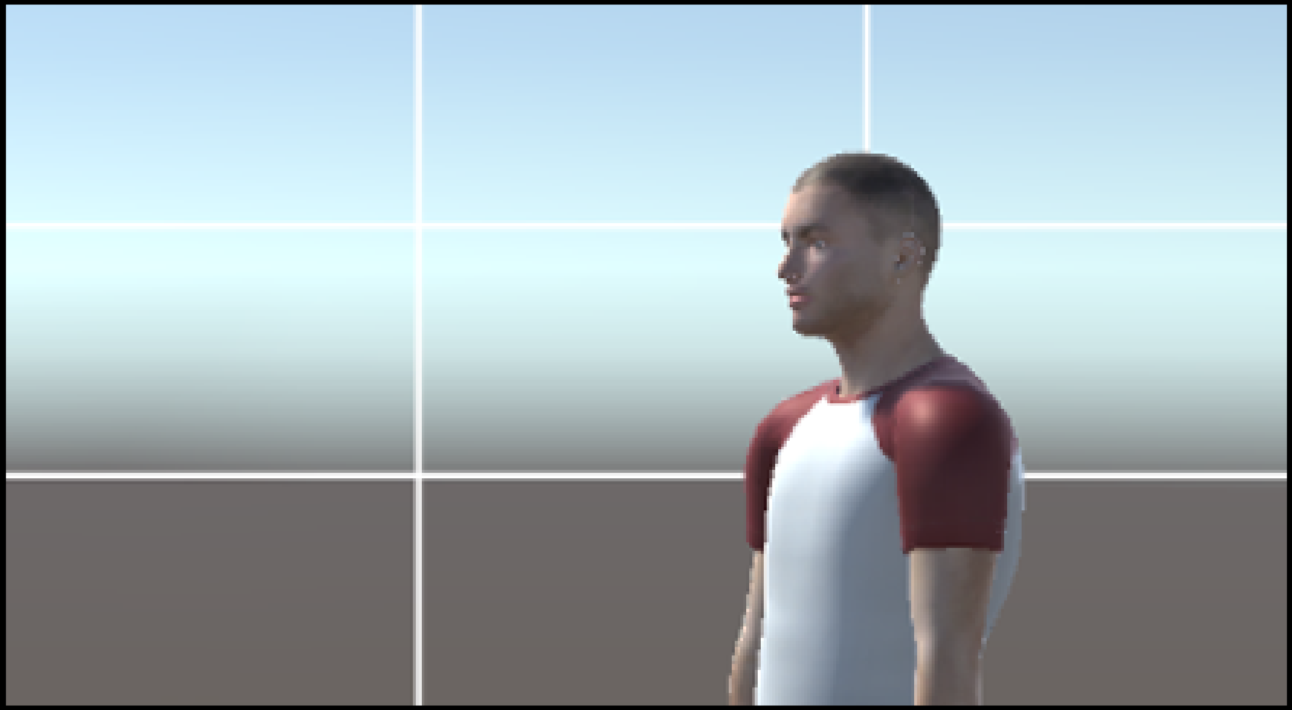
For every subject…

CANONICAL SHOTS

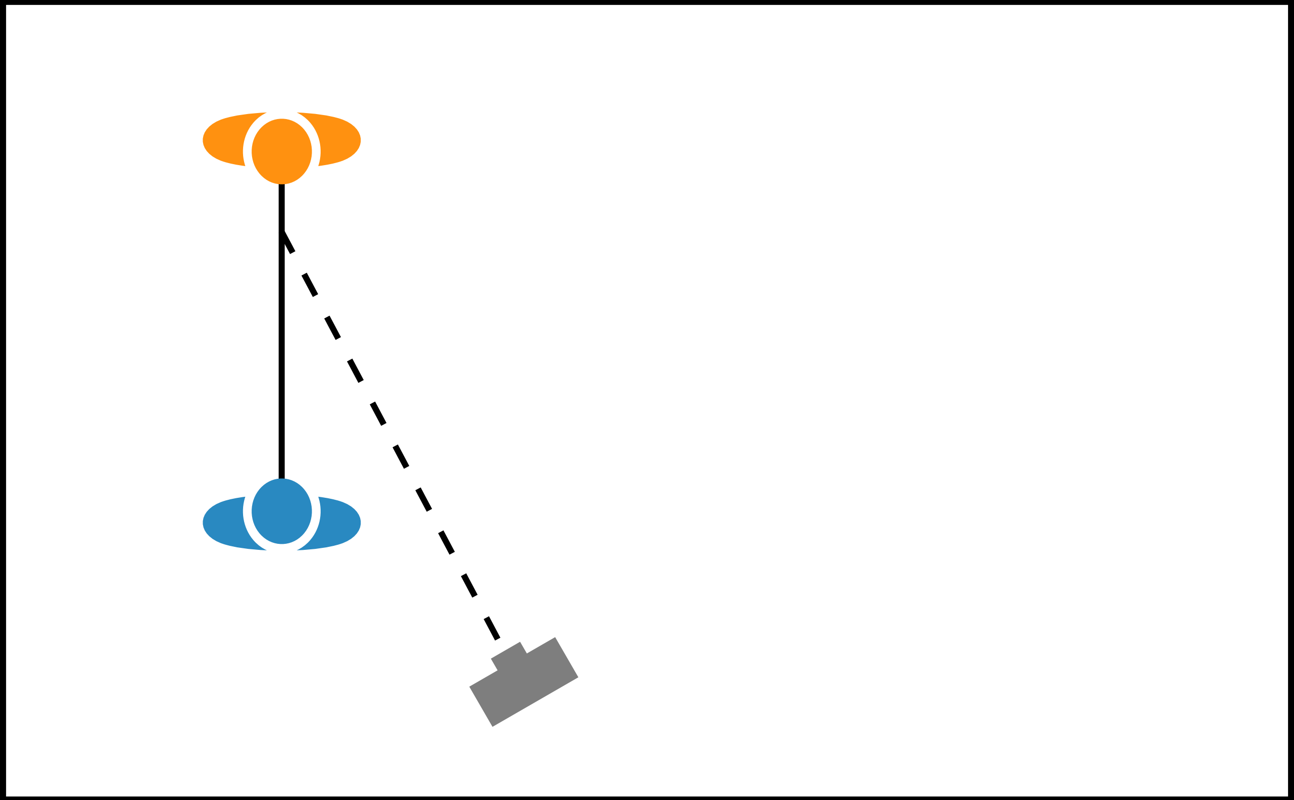
[He et al, 1999] [Rubin, 2002]

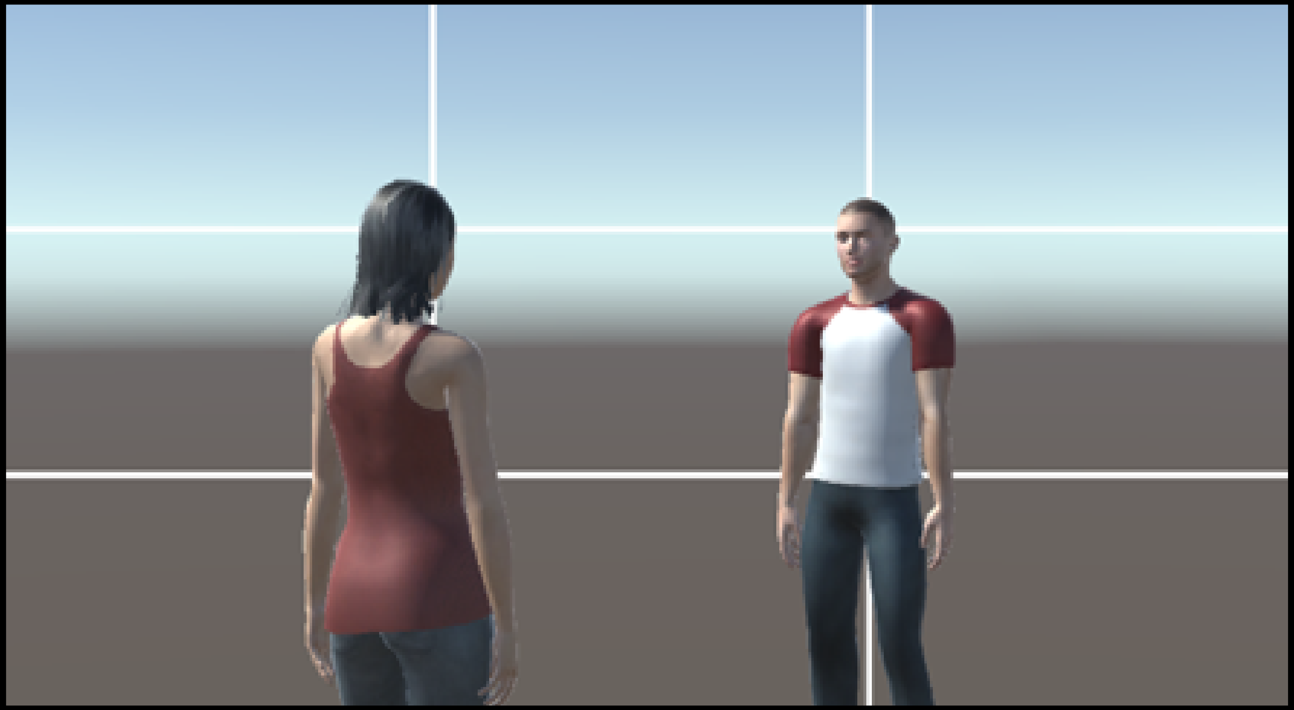
Internal





External

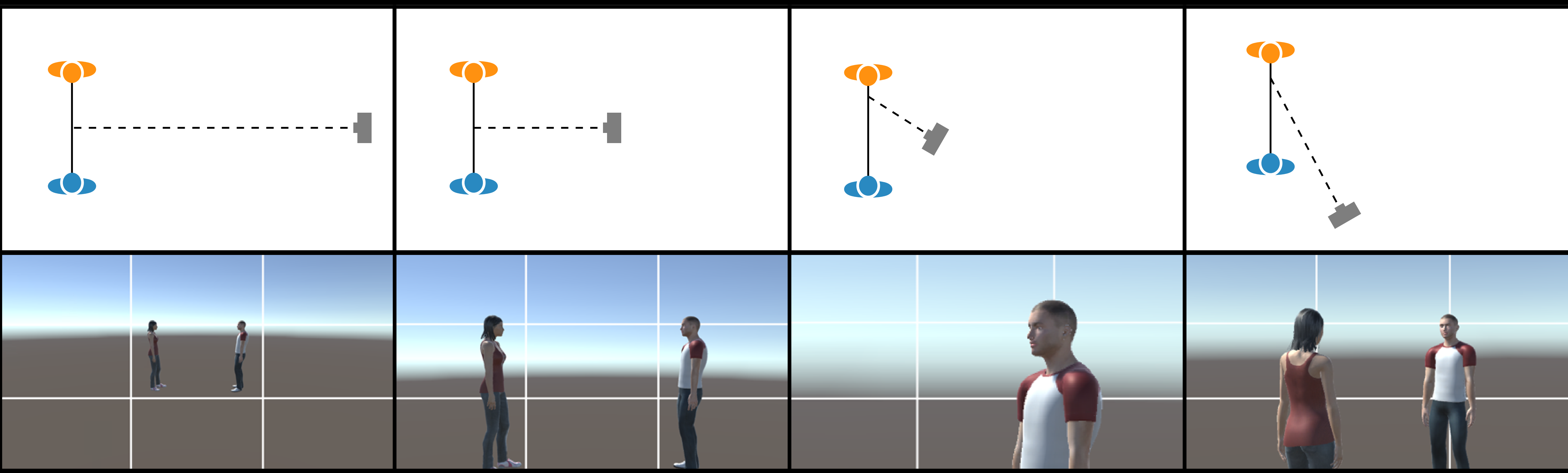




CANONICAL SHOTS

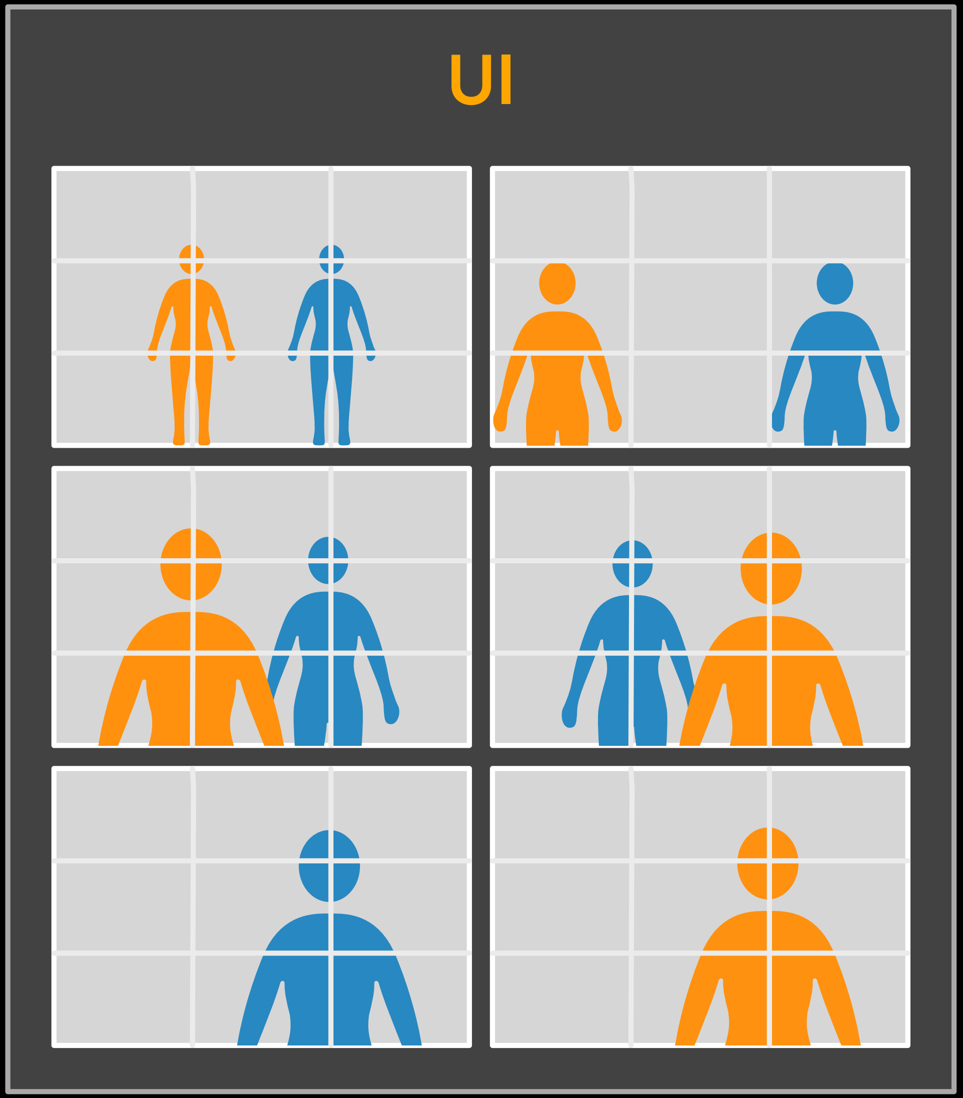
[He et al, 1999] [Rubin, 2002]

Apex | **Close Apex** | **Internal x2** | **External x2**

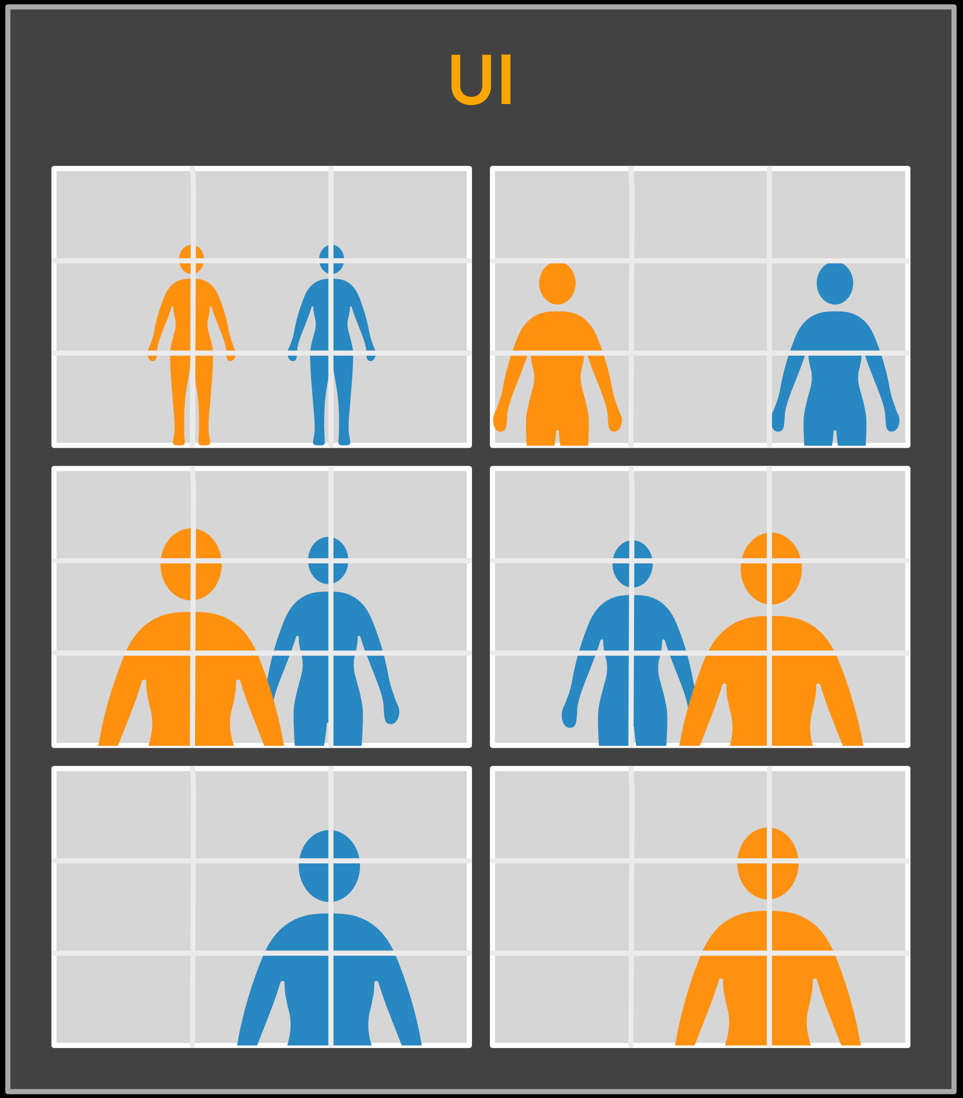


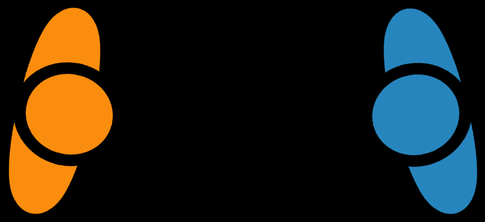
And the equivalent shots from a **higher vantage point**

USER INTERACTION

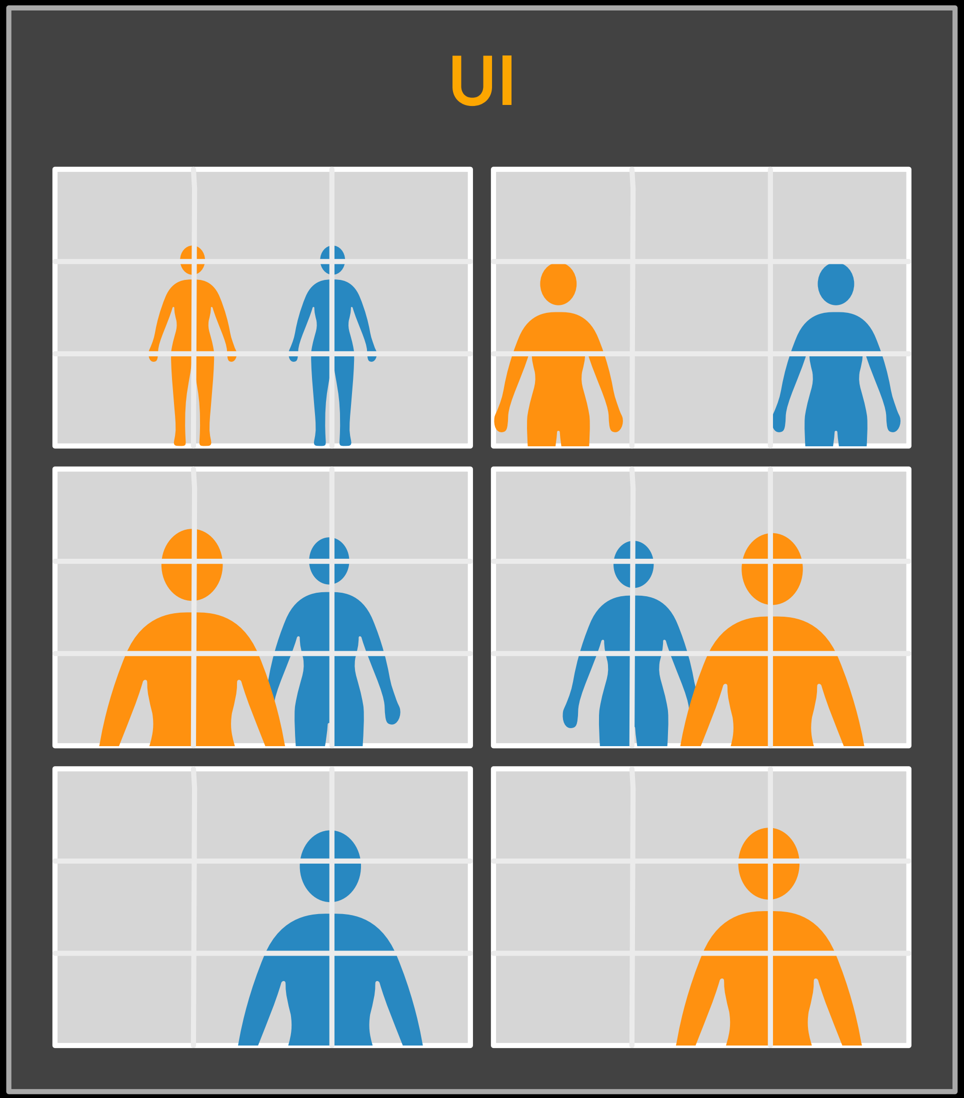


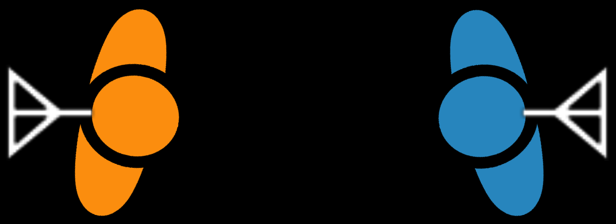
USER INTERACTION



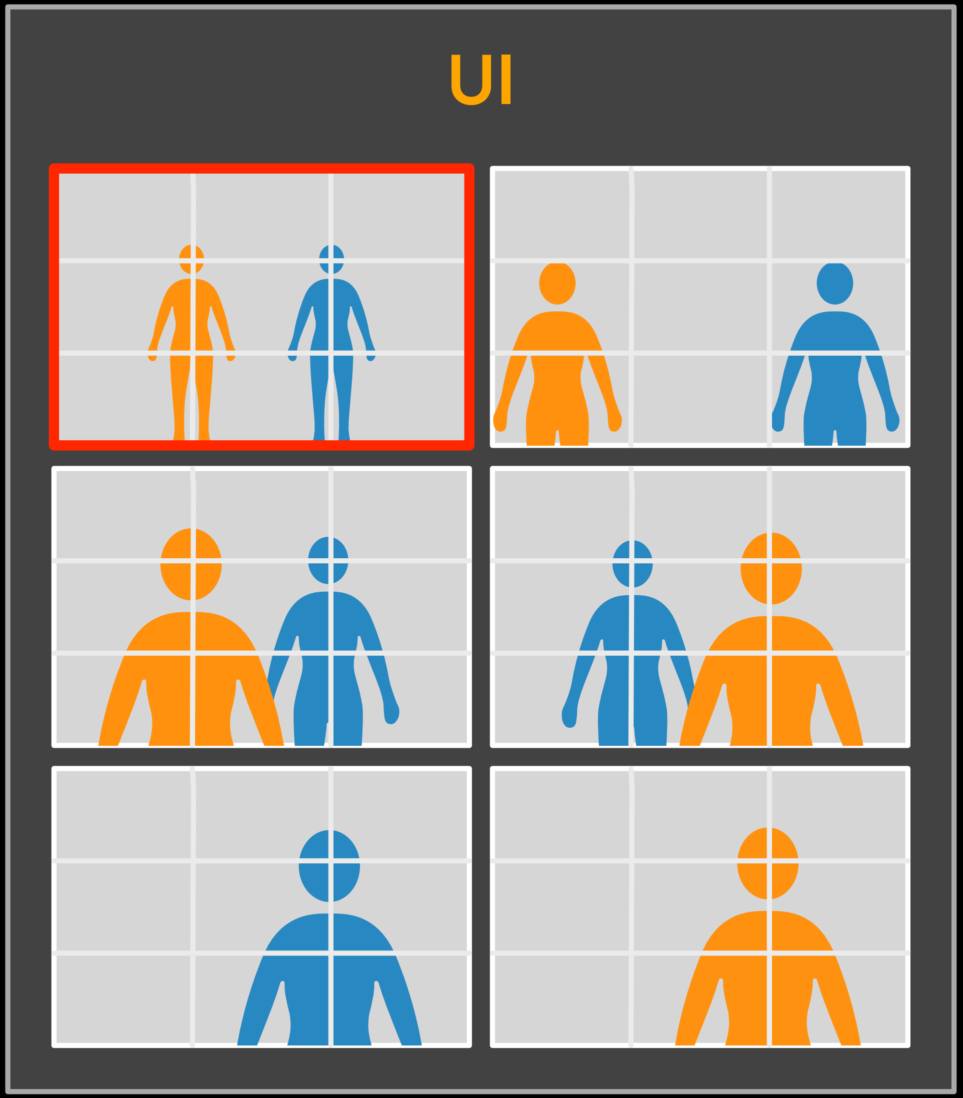


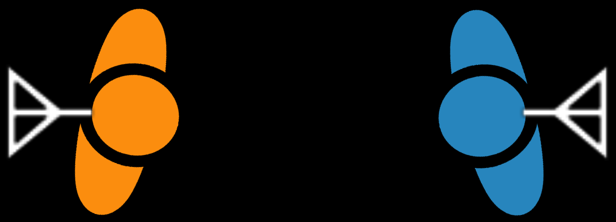
USER INTERACTION



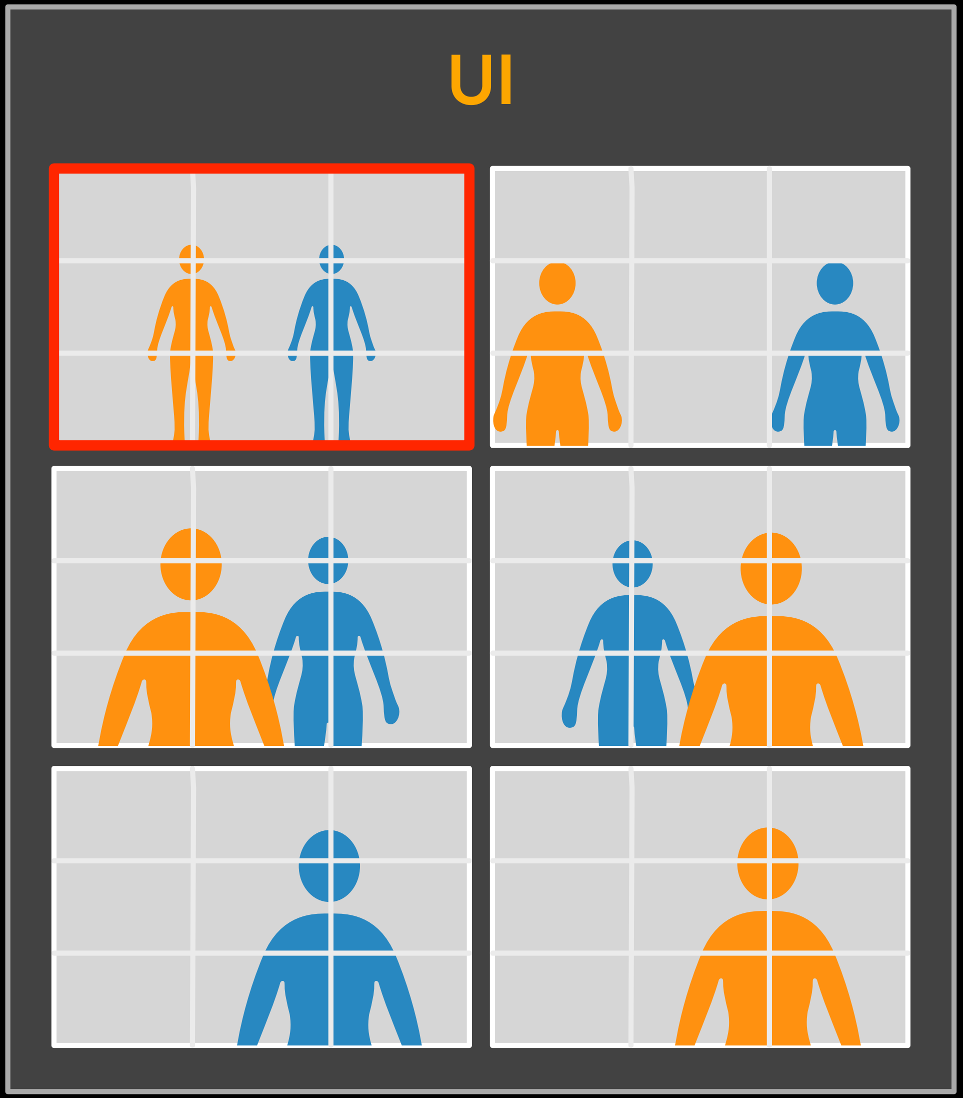


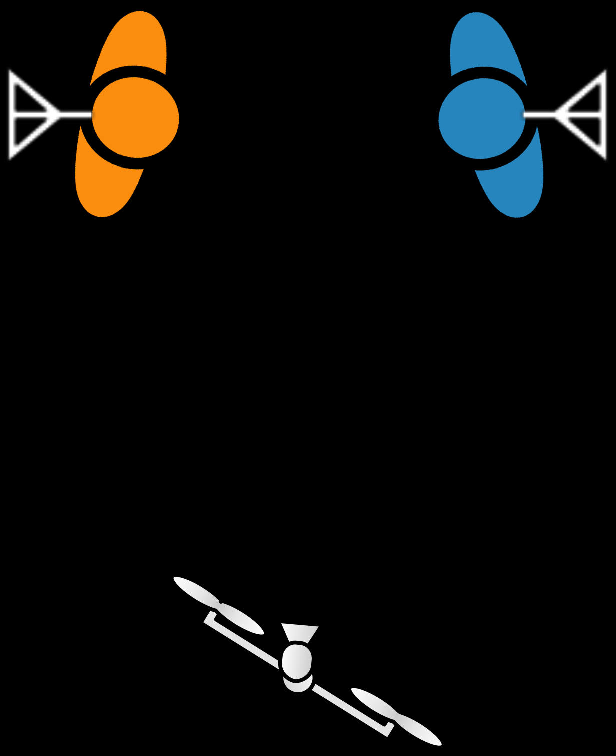
USER INTERACTION



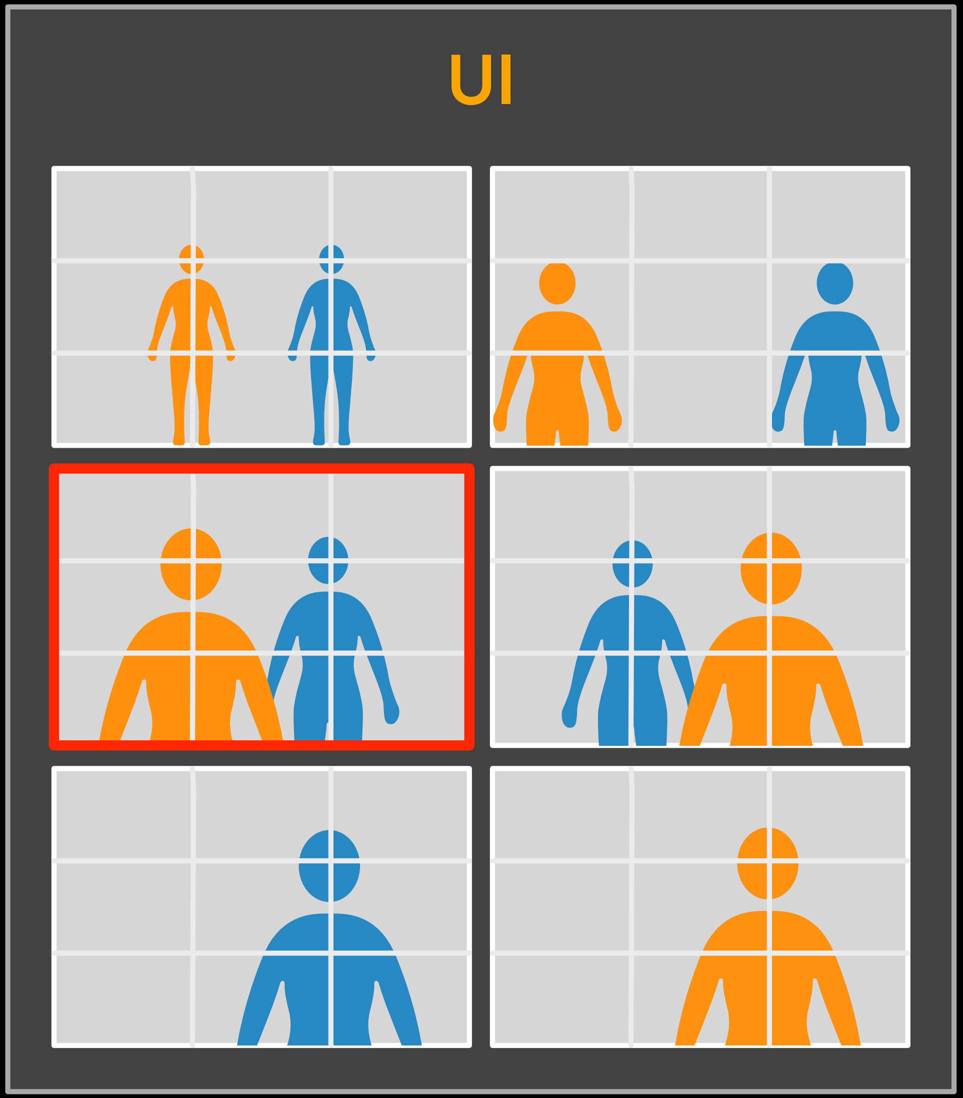


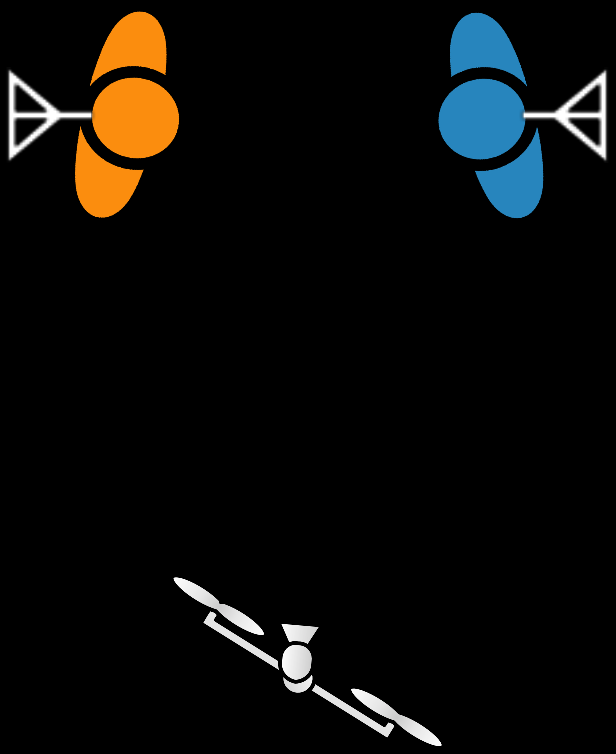
USER INTERACTION



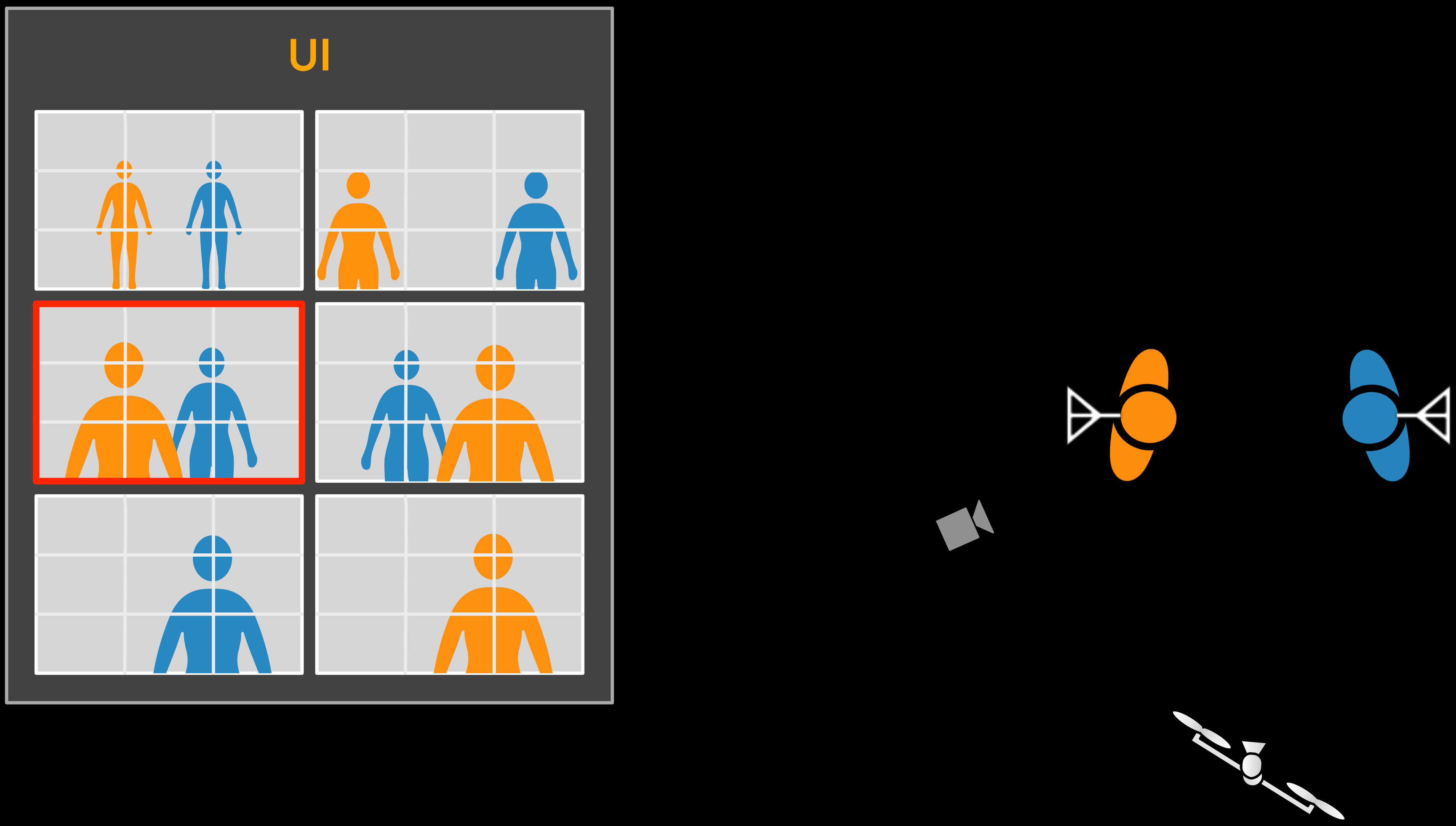


TOOL OVERVIEW

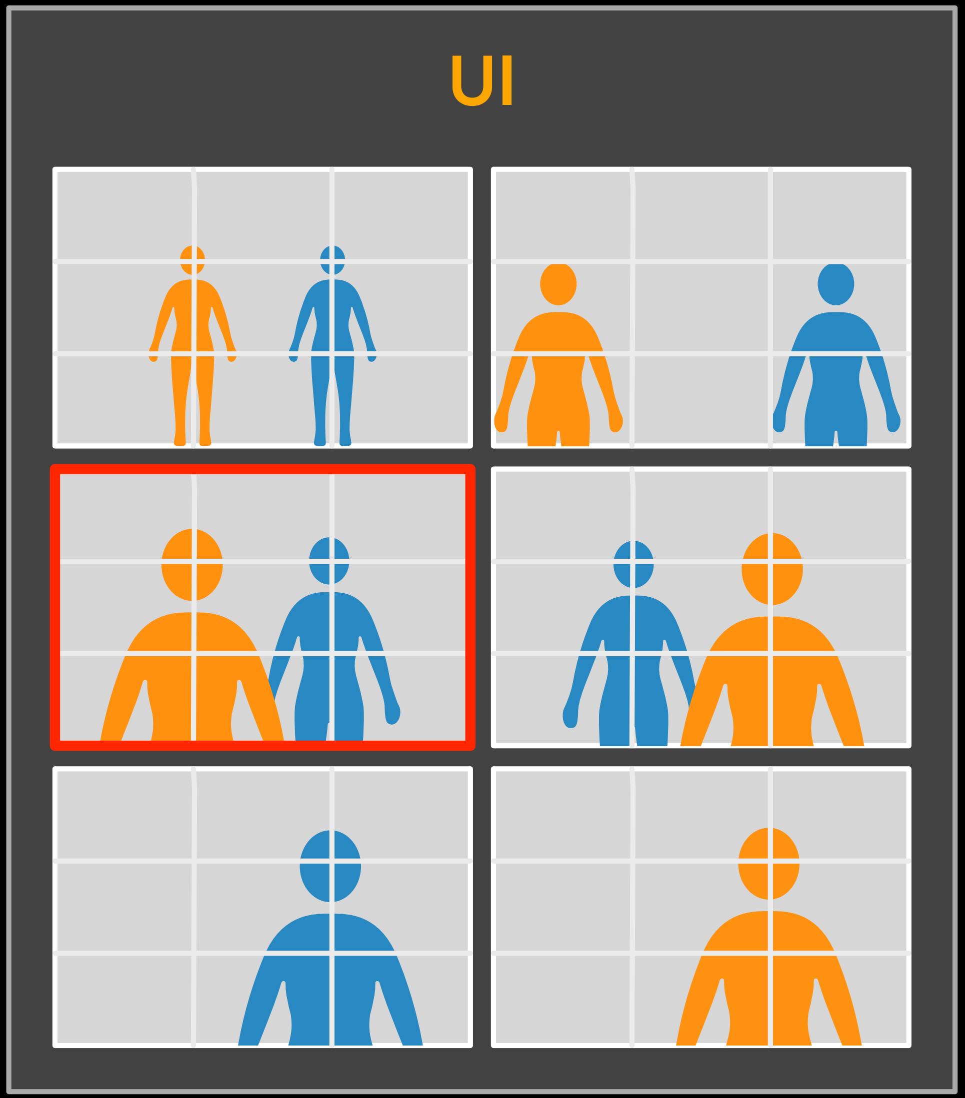


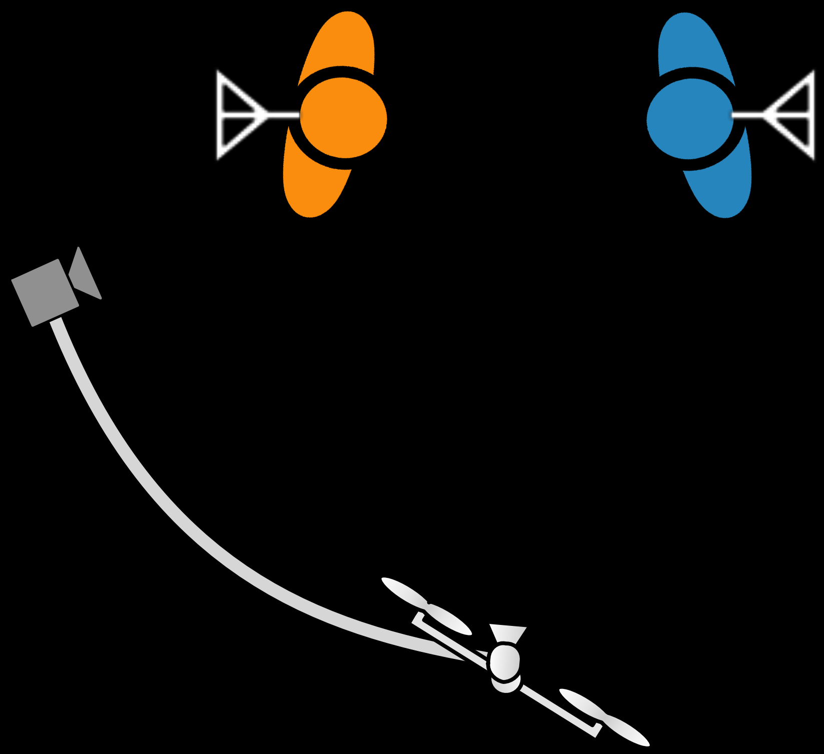


TOOL OVERVIEW

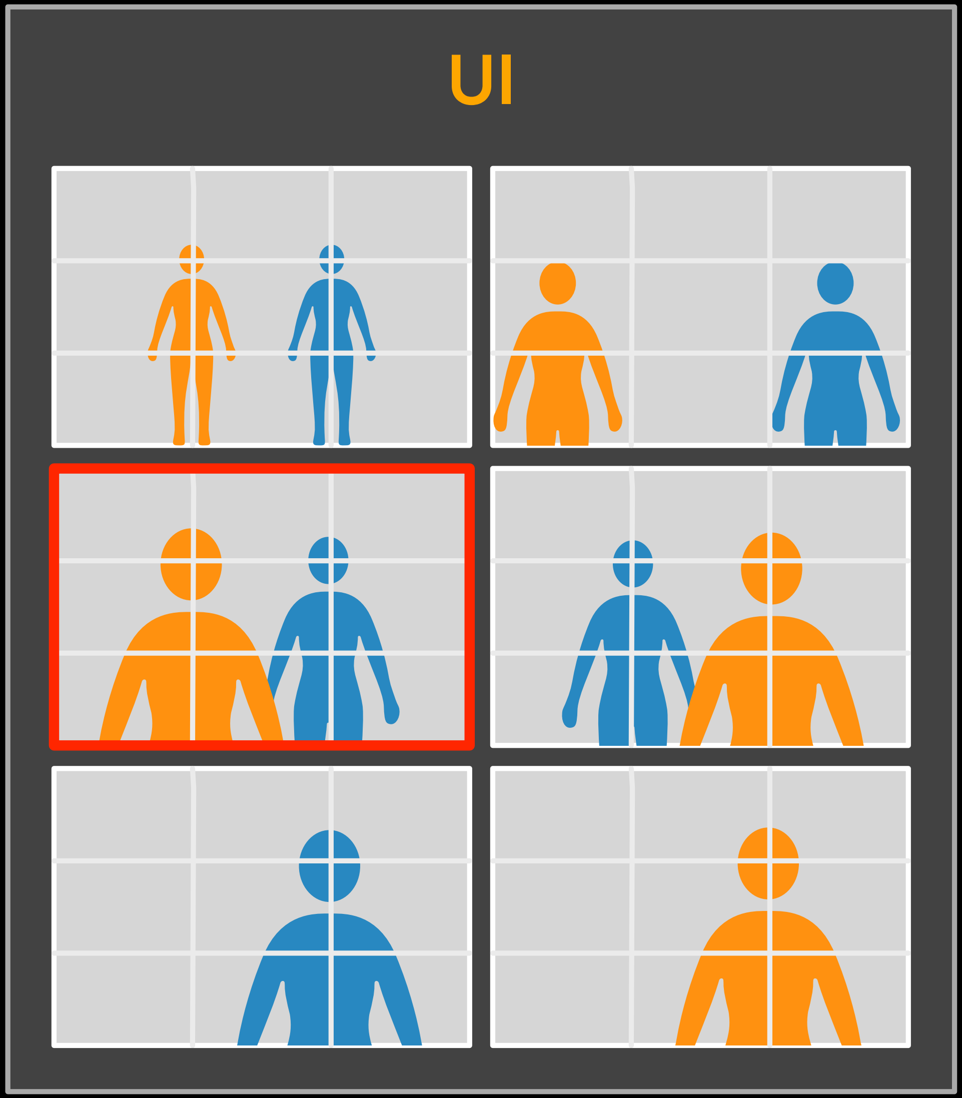


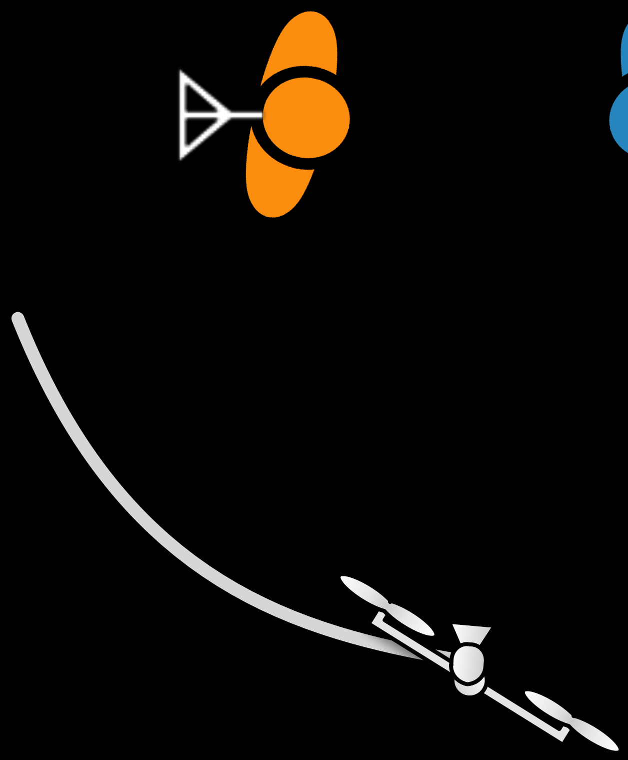
TOOL OVERVIEW





TOOL OVERVIEW





CHALLENGES

We need to **track** our subjects

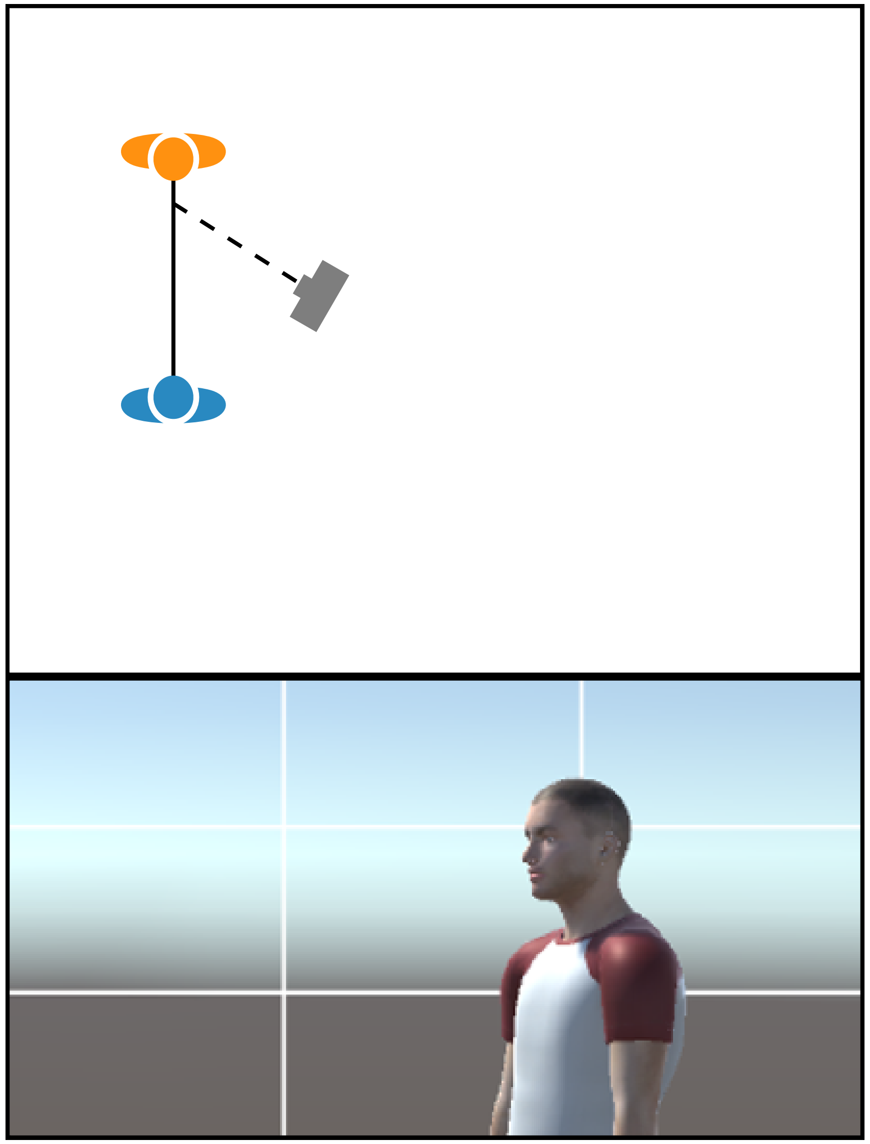
Keep our subjects **safe**

Find **high quality transitions** between shots

SAFETY

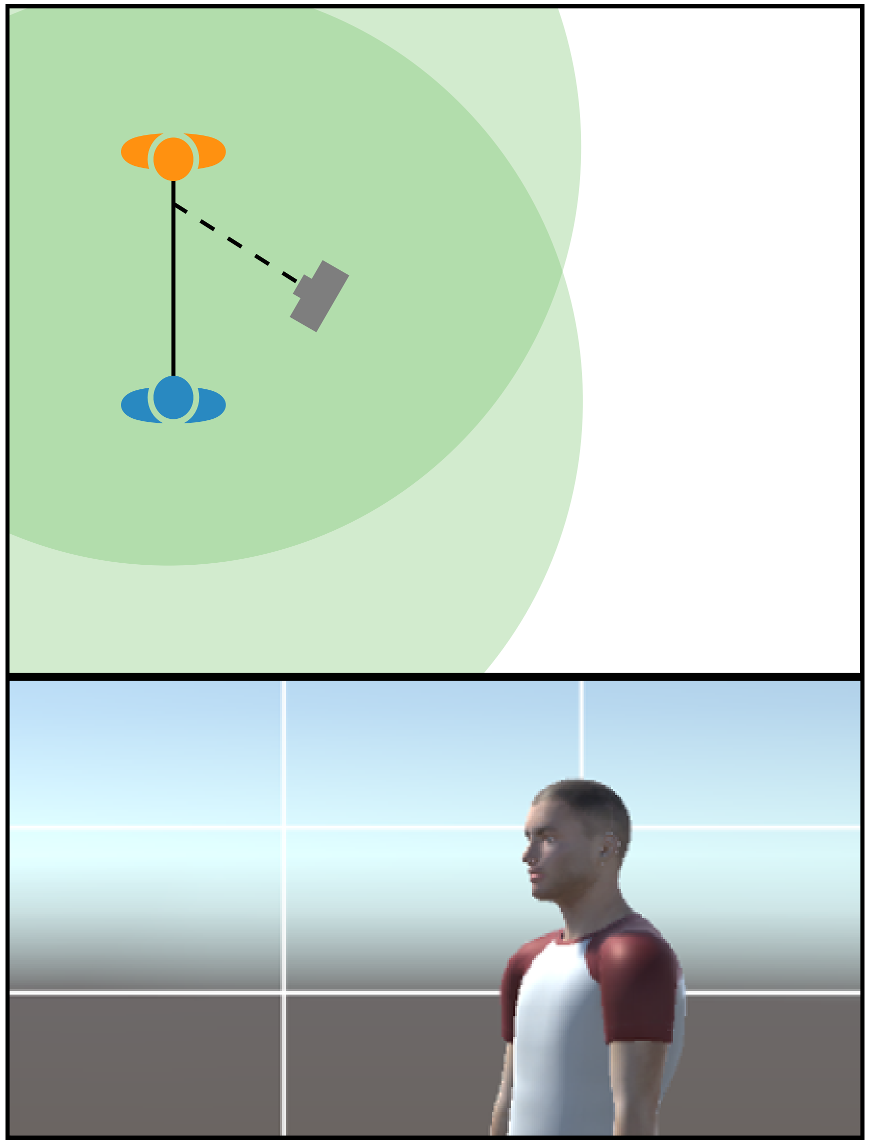
SAFETY

RESPECT A NO-FLY SPHERE



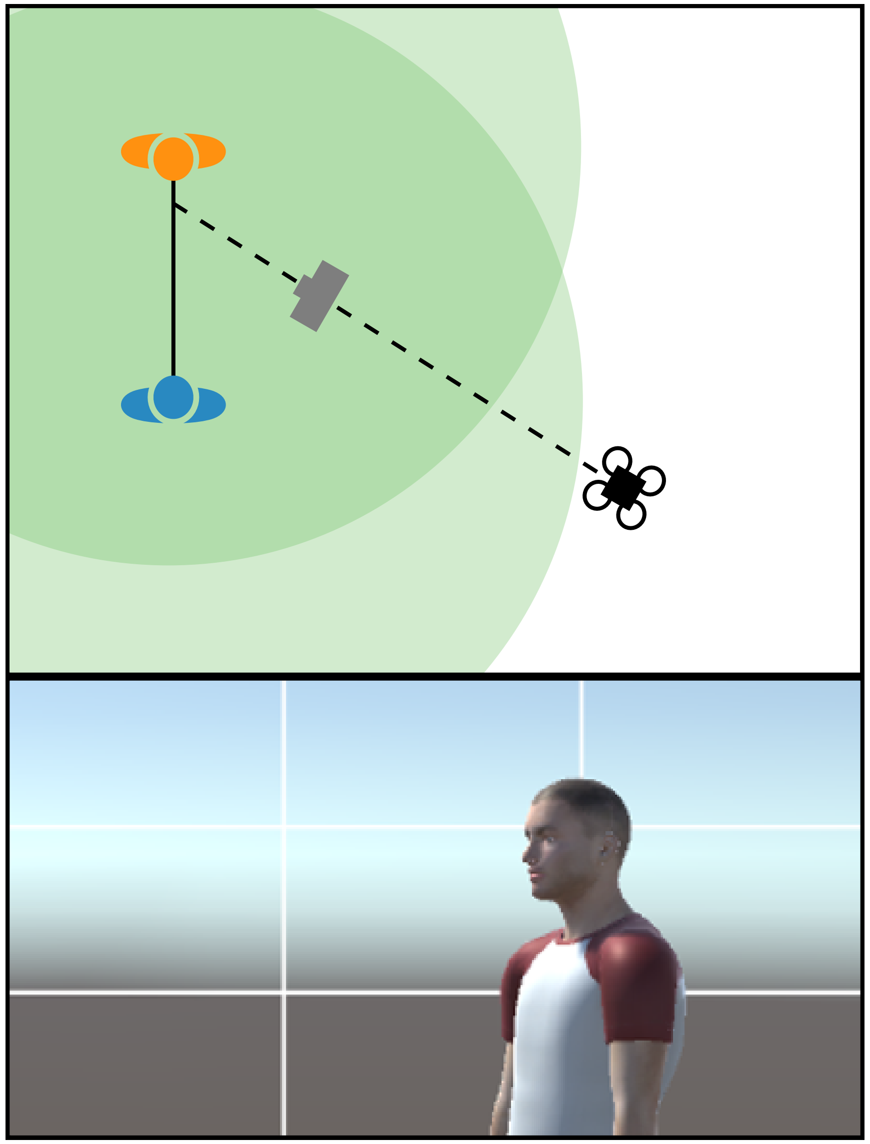
SAFETY

RESPECT A NO-FLY SPHERE



SAFETY

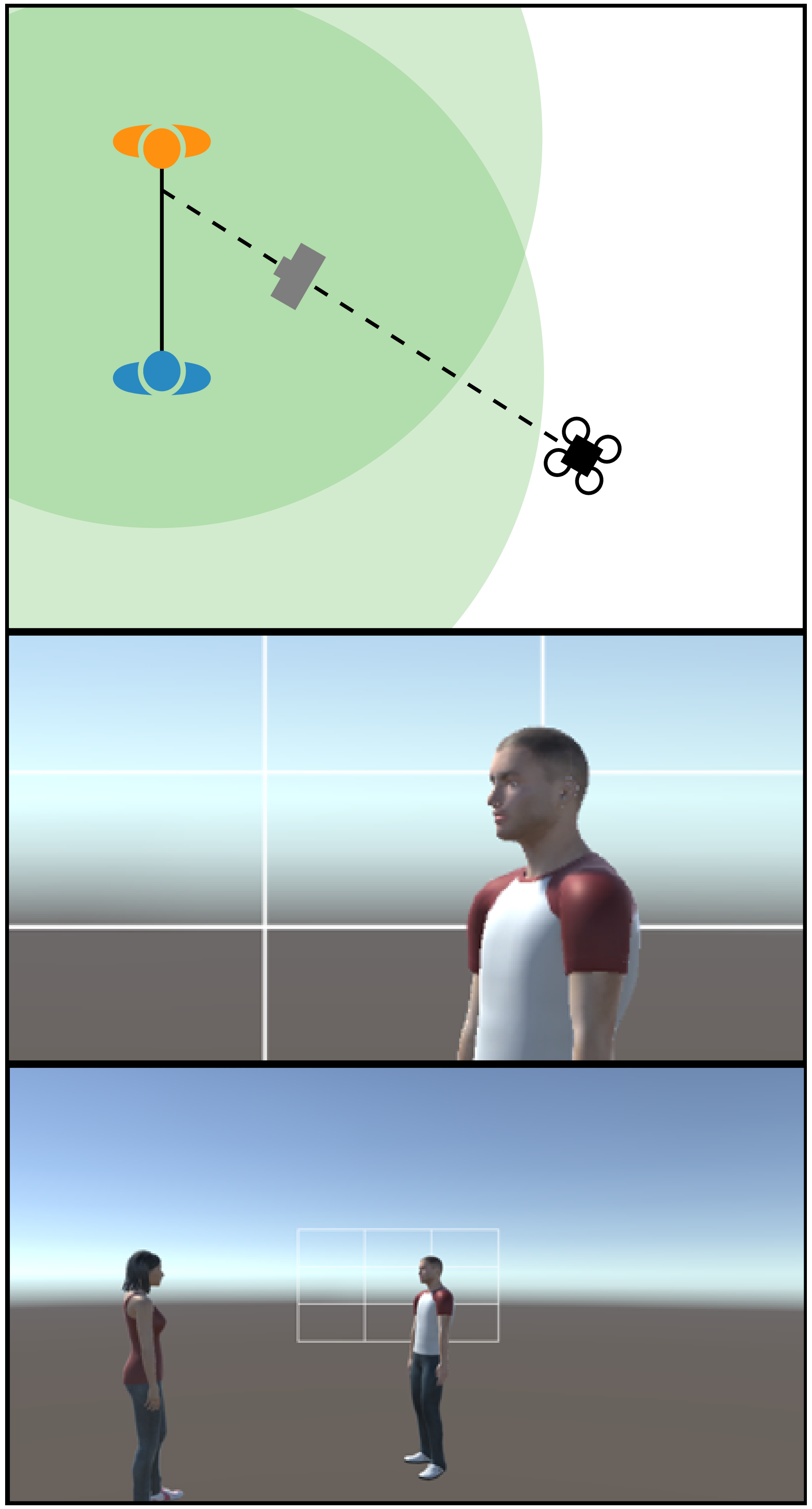
RESPECT A NO-FLY SPHERE



Push Quadrotor Out

SAFETY

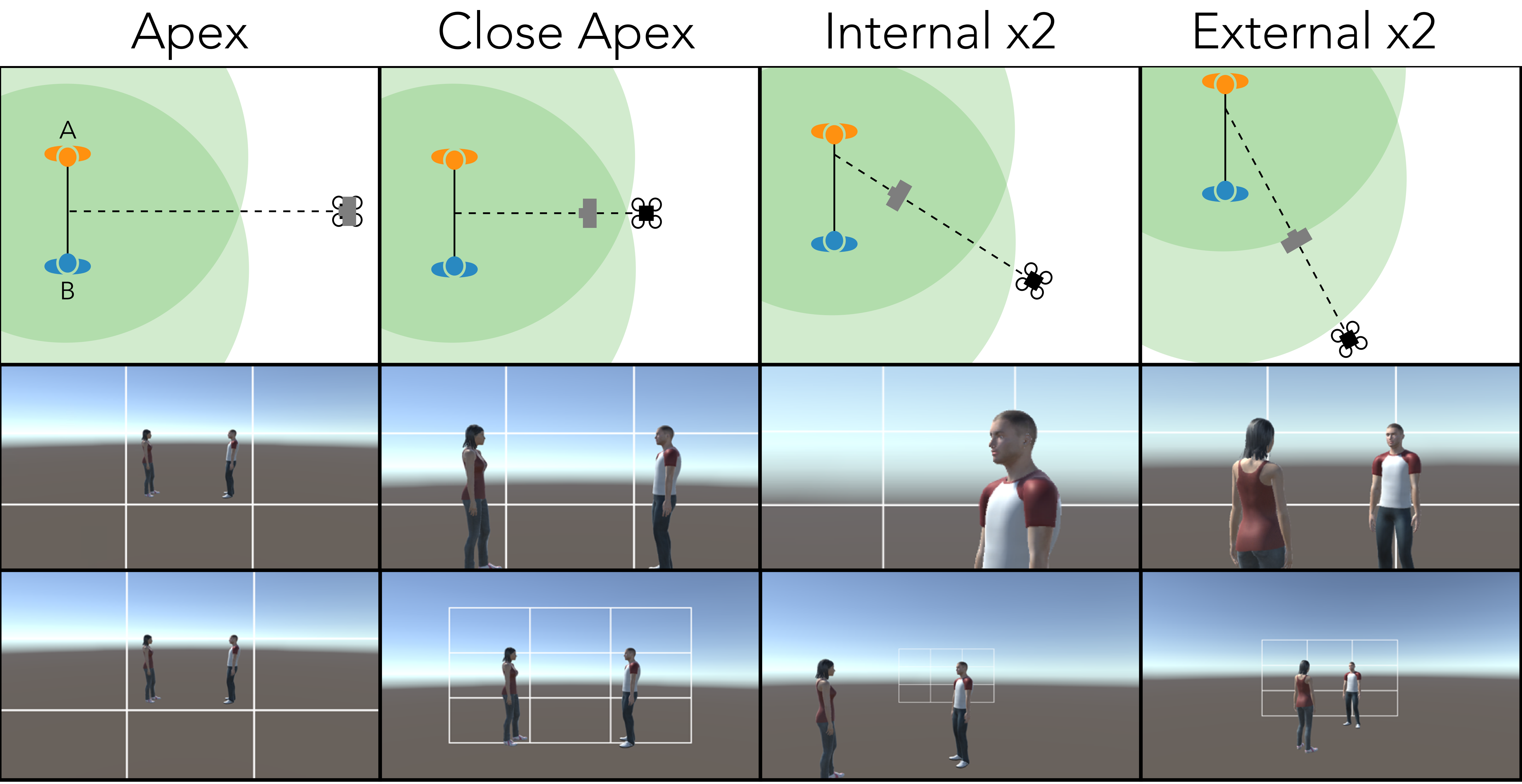
RESPECT A NO-FLY SPHERE



Push Quadrotor Out

Crop or Zoom Camera

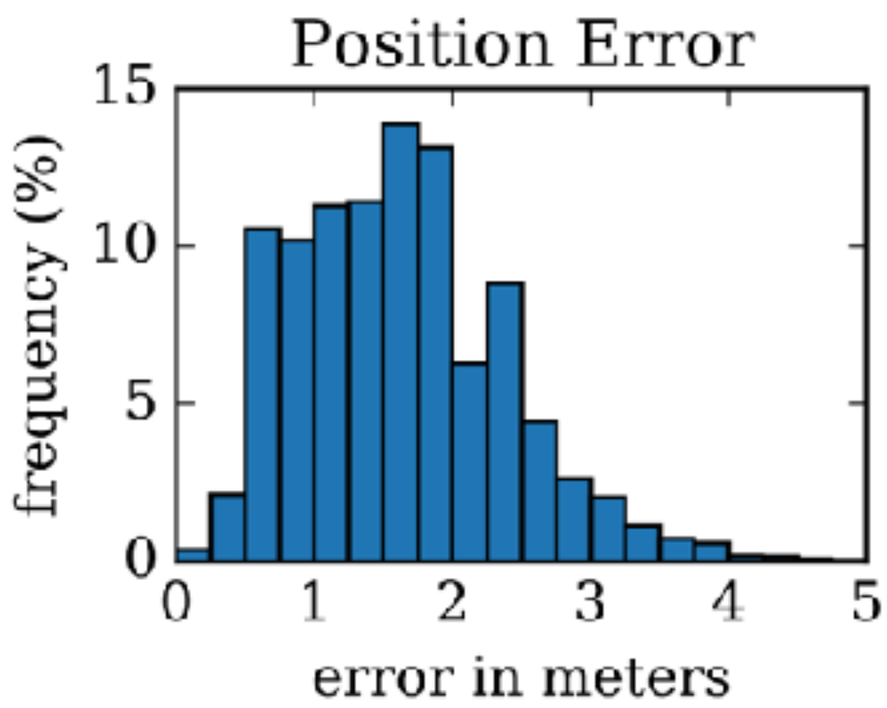
SAFETY
ADAPT CANONICAL SHOTS

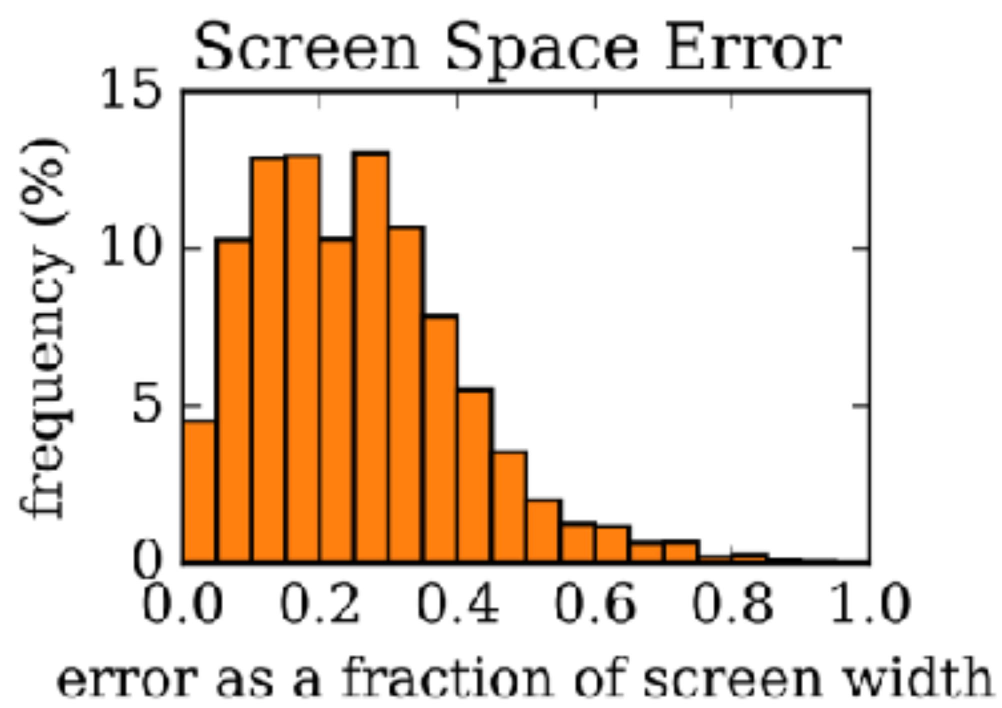


TRACKING

TRACKING

CAN WE USE CONVENTIONAL GPS?





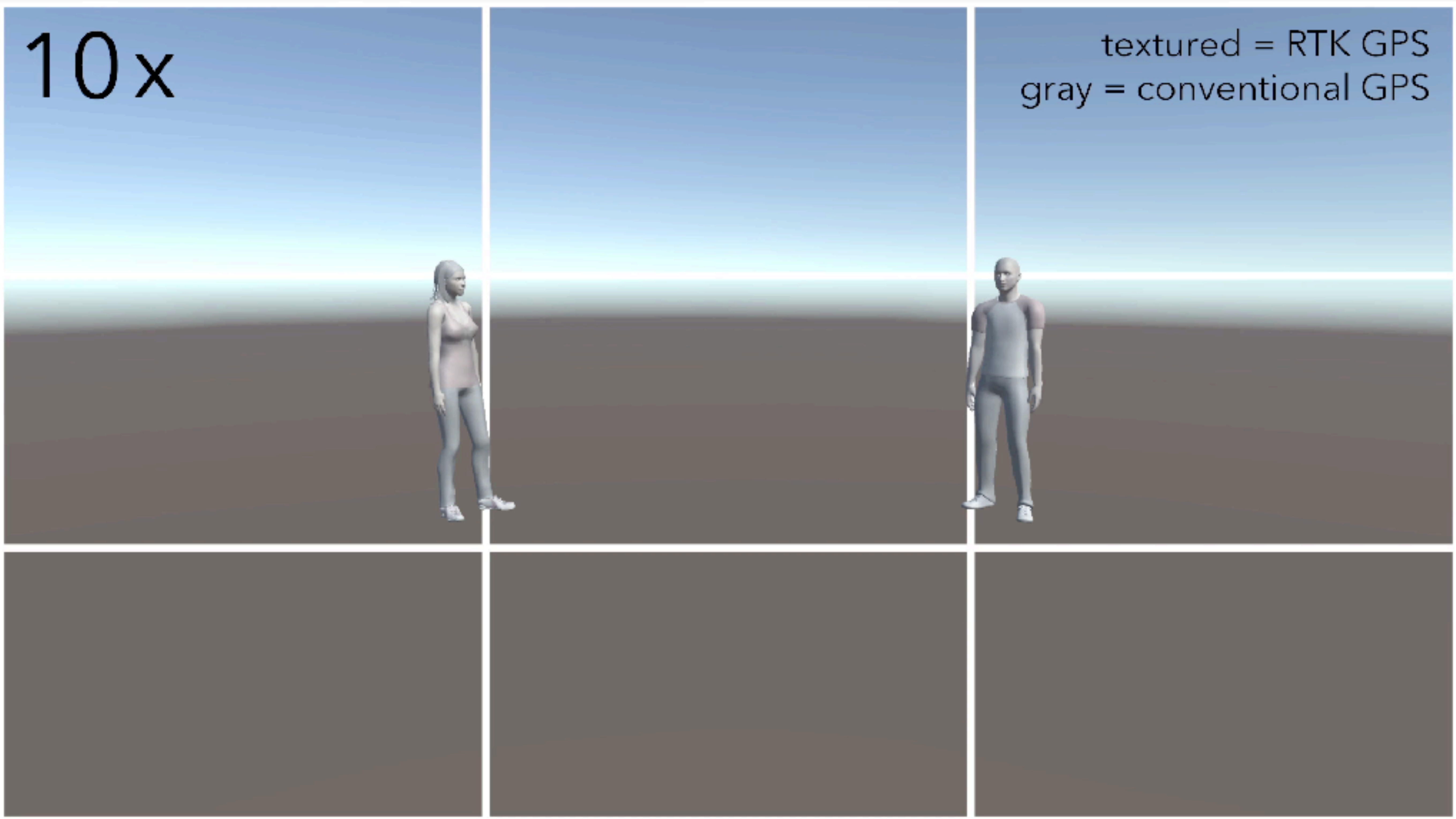
Not accurate enough!

TRACKING
A CENTIMETER ACCURATE GPS TESTBED

RTK-GPS vs Conventional GPS
Tracking Position Accuracy

	Ours	Conventional
North-East CEP_{95}	0.017 m	1.68 m
Altitude Std. Dev.	0.020 m	0.108 m
Distance Error after Loop Closure	0.011 m	1.058 m

TRACKING
A CENTIMETER ACCURATE GPS TESTBED

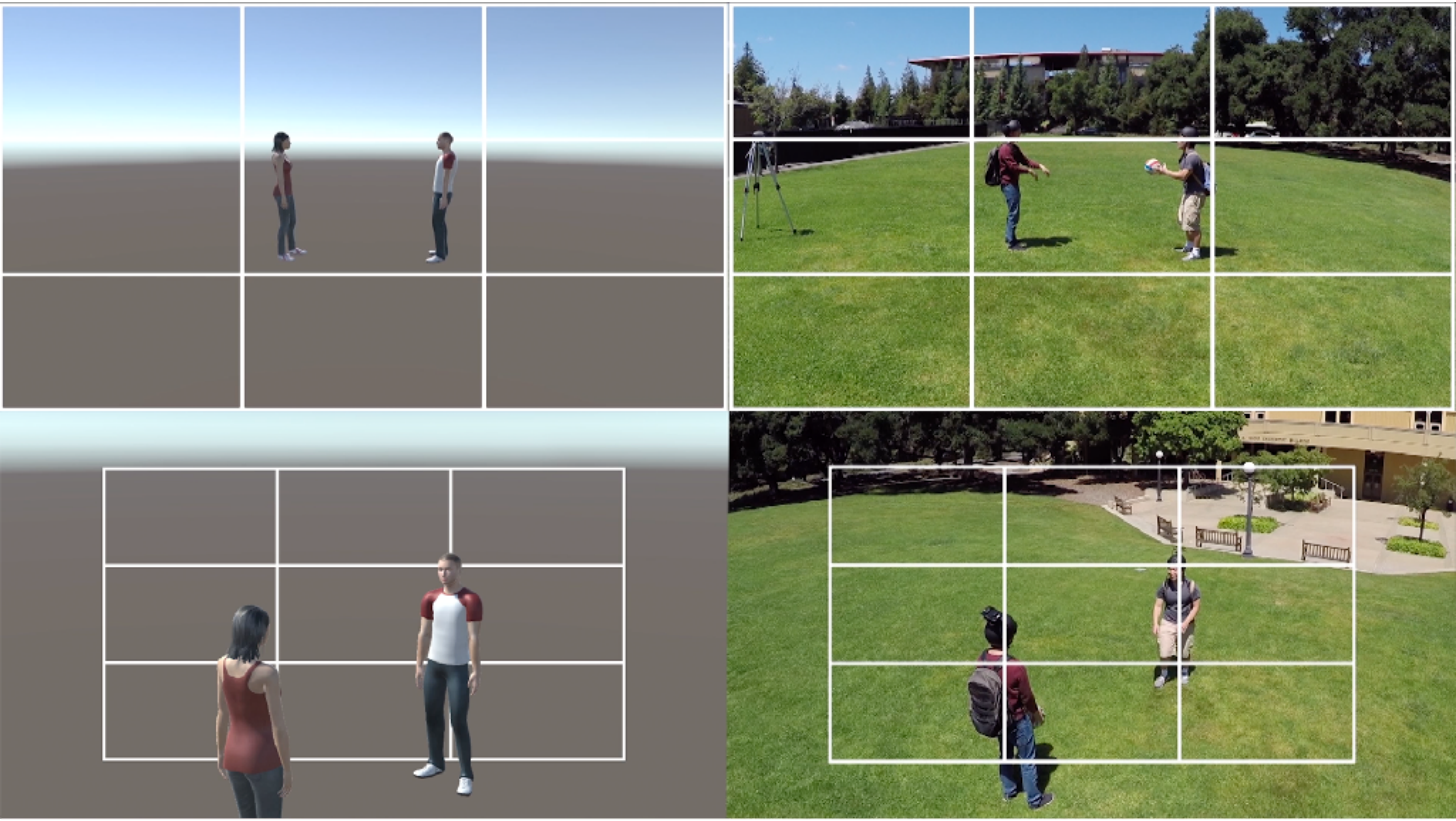


TRACKING

END-TO-END SYSTEM

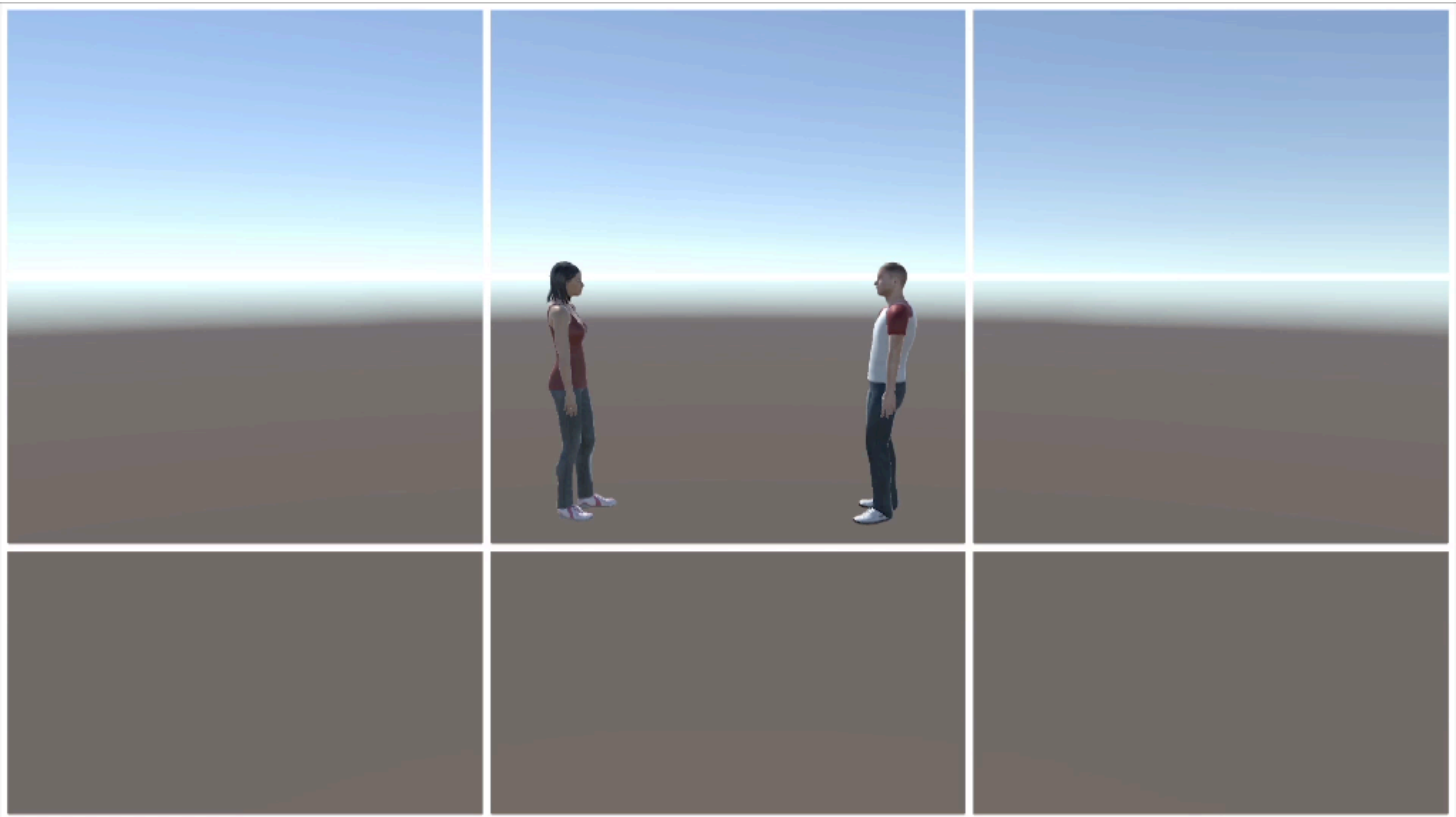
RESULTS

SAFE STATIC SHOTS, ACCURATE TRACKING

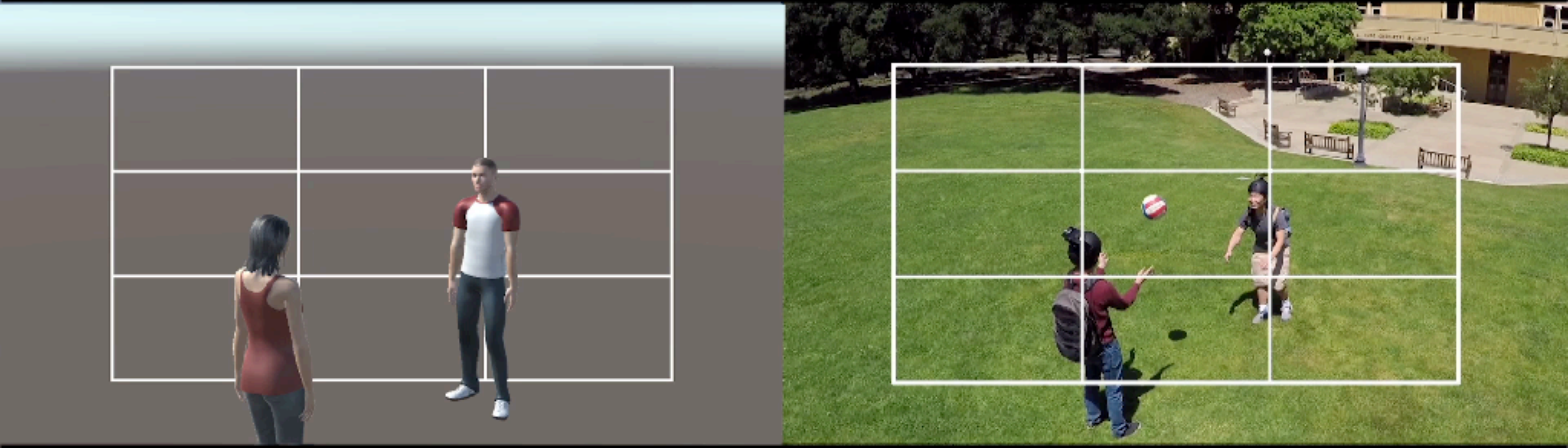


RESULTS

SAFE STATIC SHOTS, ACCURATE TRACKING



RESULTS
SAFE STATIC SHOTS, ACCURATE TRACKING



RESULTS

SAFE STATIC SHOTS, ACCURATE TRACKING

TRANSITIONS

How do we move the quadrotor camera between static shots?

Can we use the trajectories from Horus?

SIMPLY USING HORUS TRAJECTORIES DOESN'T WORK

TRANSITIONS

We must move the quadrotor in a way that is

feasible

safe

produces **visually pleasing** video

and find such a trajectory **on demand, in real-time**

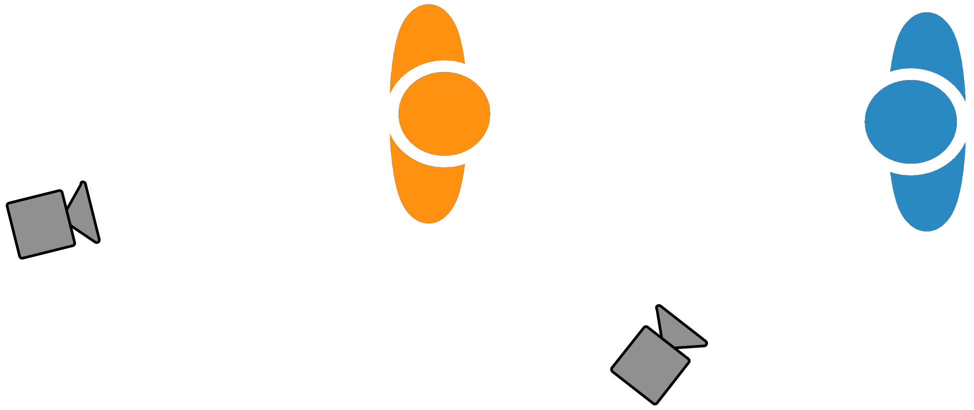
TRANSITIONS

USE THE TORIC SPACE METHOD?

[Lino and Christie, SIGGRAPH, 2015]

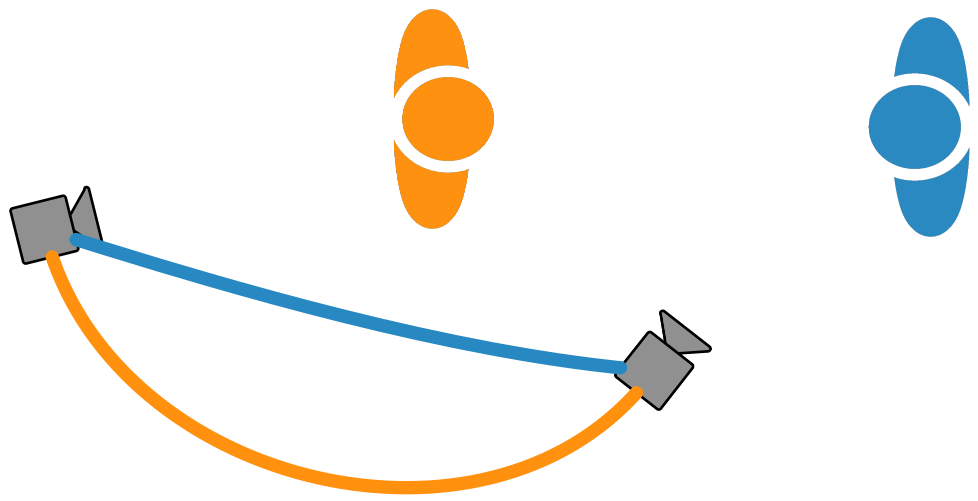
TRANSITIONS

INSPECT THE TORIC SPACE METHOD



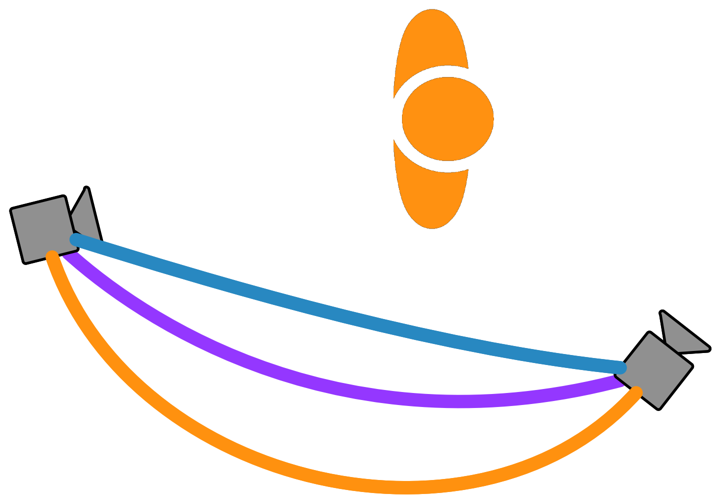
TRANSITIONS

INSPECT THE TORIC SPACE METHOD



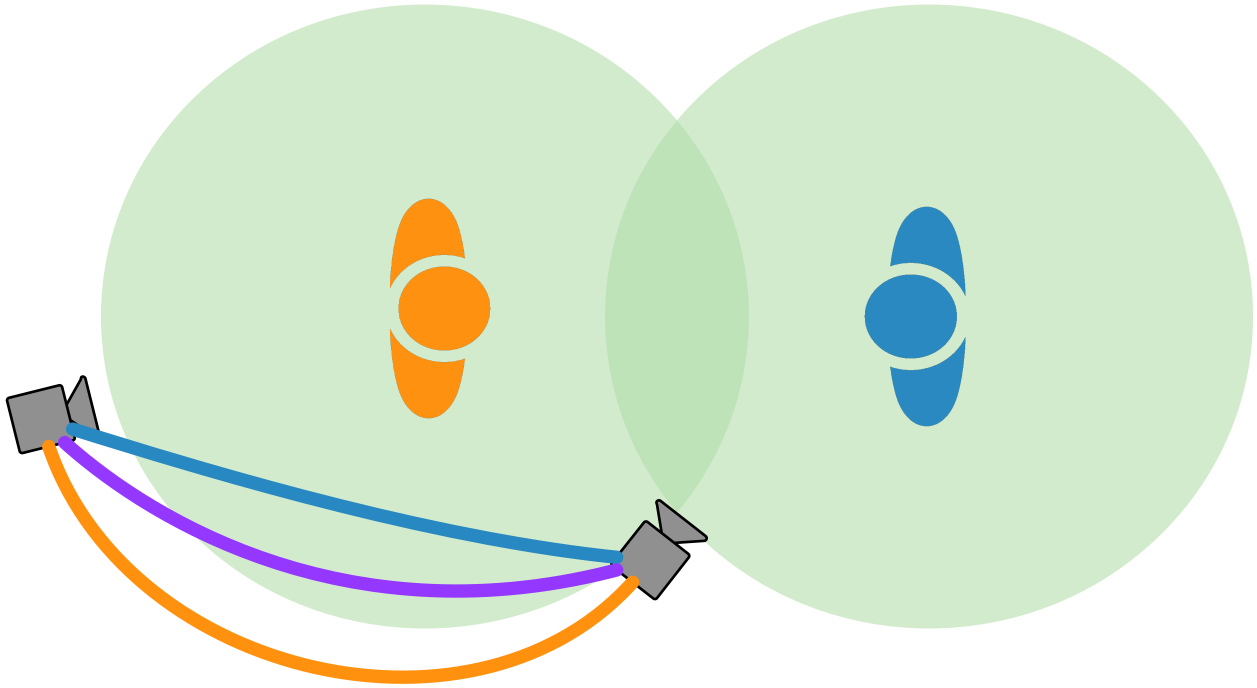
TRANSITIONS

INSPECT THE TORIC SPACE METHOD



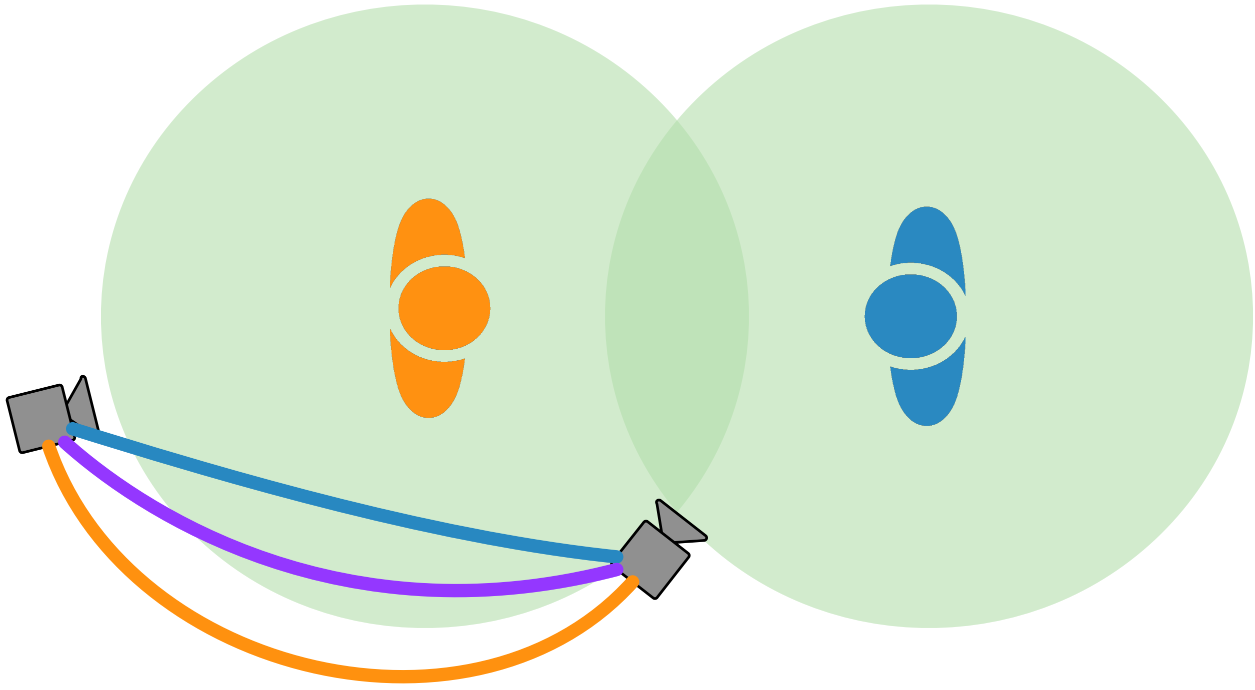
TRANSITIONS

INSPECT THE TORIC SPACE METHOD



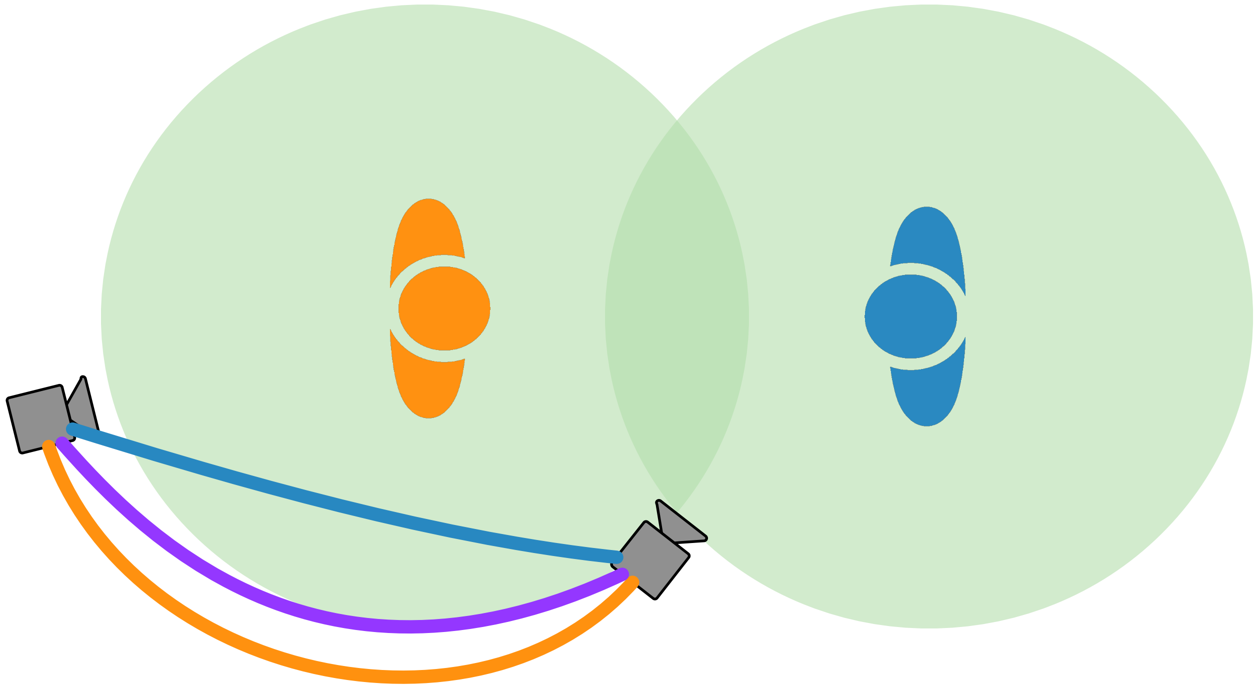
TRANSITIONS

INSPECT THE TORIC SPACE METHOD



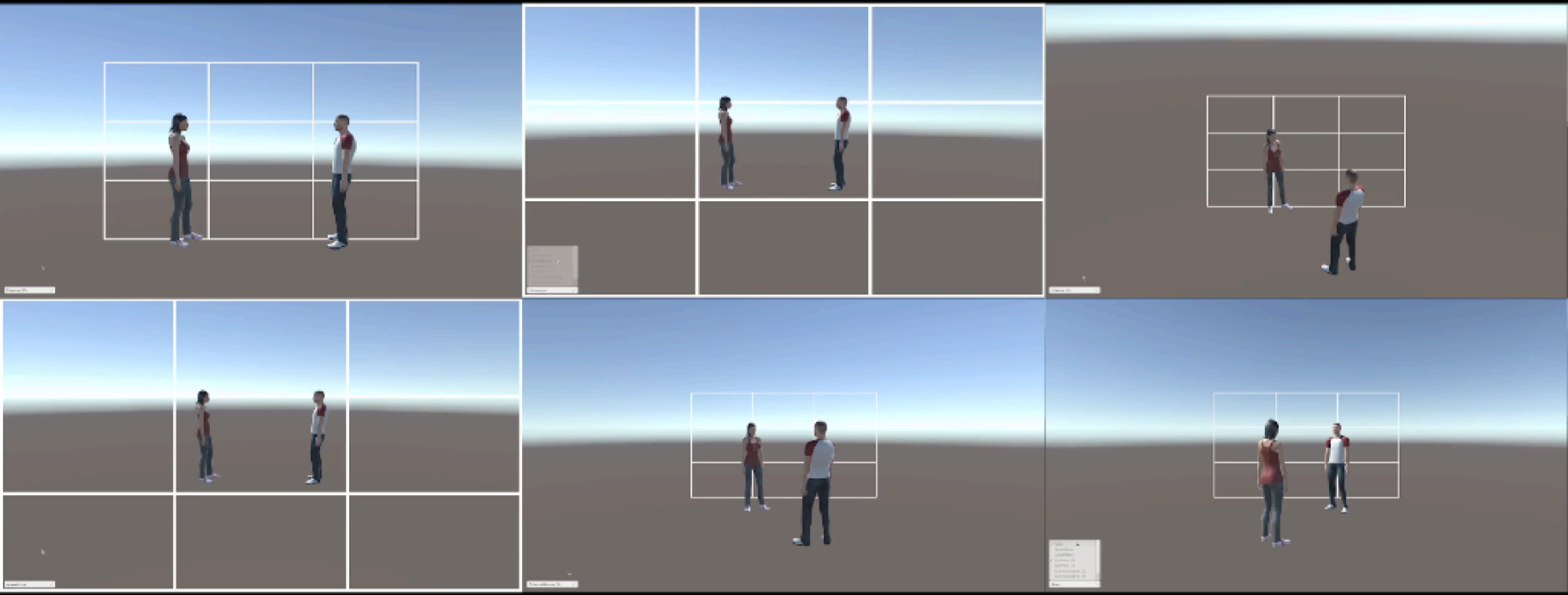
TRANSITIONS

INSPECT THE TORIC SPACE METHOD



RESULT: SAFE, FEASIBLE AND VISUALLY PLEASING TRANSITIONS

RESULT: SAFE, FEASIBLE AND VISUALLY PLEASING TRANSITIONS



WE CAN AUTOMATICALLY CAPTURE SEQUENCES OF WELL-COMPOSED SHOTS

SUMMARY

We automated **high quality visual compositions**

We adapted canonical shots to ensure **safety**

We validated, and then **tracked** our subjects, using state-of-the-art RTK-GPS

We introduced a **real-time trajectory planning algorithm** to find visually pleasing, safe and feasible transitions.

WITH THE DRONE CINEMATOGRAPHER,
THE USER ACTS AS A DIRECTOR.

OVERVIEW

Compose shots using classic 3D Animation primitives, adapted to respect quadrotor camera physics [SIGASIA 2015]

Horus

A Tool for Shot Planning

Compose shots in real time using visual composition principles from filmmaking [arXiv 2016]

Drone Cinematographer

A Tool for Filming People

CONTRIBUTIONS

Horus

[SIGASIA 2015]

Proved C4 continuous look-at look-from trajectories and progress curves satisfy Quadrotor Camera equations of motion

Showed that Computer Graphics primitives enable users to capture high quality quadrotor shots, even if they're novices

Drone Cinematographer

[arXiv 2016]

Adapt canonical cinematography shots to ensure safety

Track subjects with high enough accuracy for cinematography using RTK-GPS

Showed how to find visually pleasing and safe trajectories
for quadrotor cameras filming people

CINEMATOGRAPHY-FIRST INTERACTION

We **automated the role of the pilot**

Provided tools that enabled novice and experts alike
to **capture impressive cinematography**

by incorporating **quadrotor demands**
into **cinematography primitives**

THE FUTURE IS BRIGHT!

Plenty of other cinematography primitives

“Through the lens” drone control?

Exciting new tracking and control systems

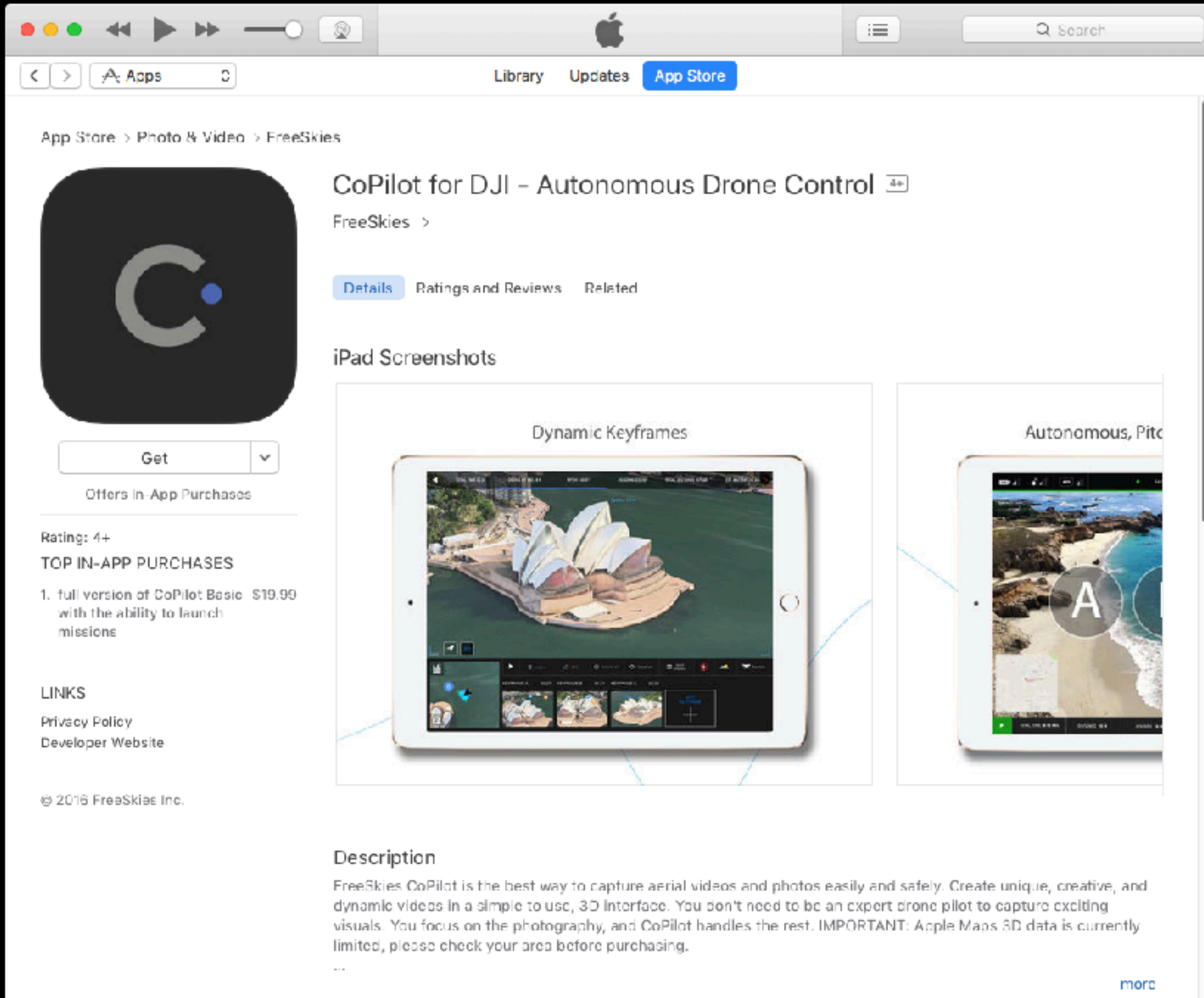
Ultra-Wideband short range tracking? Multi-sensor fusion?

Hyper-agile quadrotors!

10g and 20g quadrotors? 400ft in under 1 second

Creative uses of drones beyond cinematography

IMPACT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Rating: 4+
TOP IN-APP PURCHASES
1. full version of CoPilot Basic with the ability to launch missions $19.99
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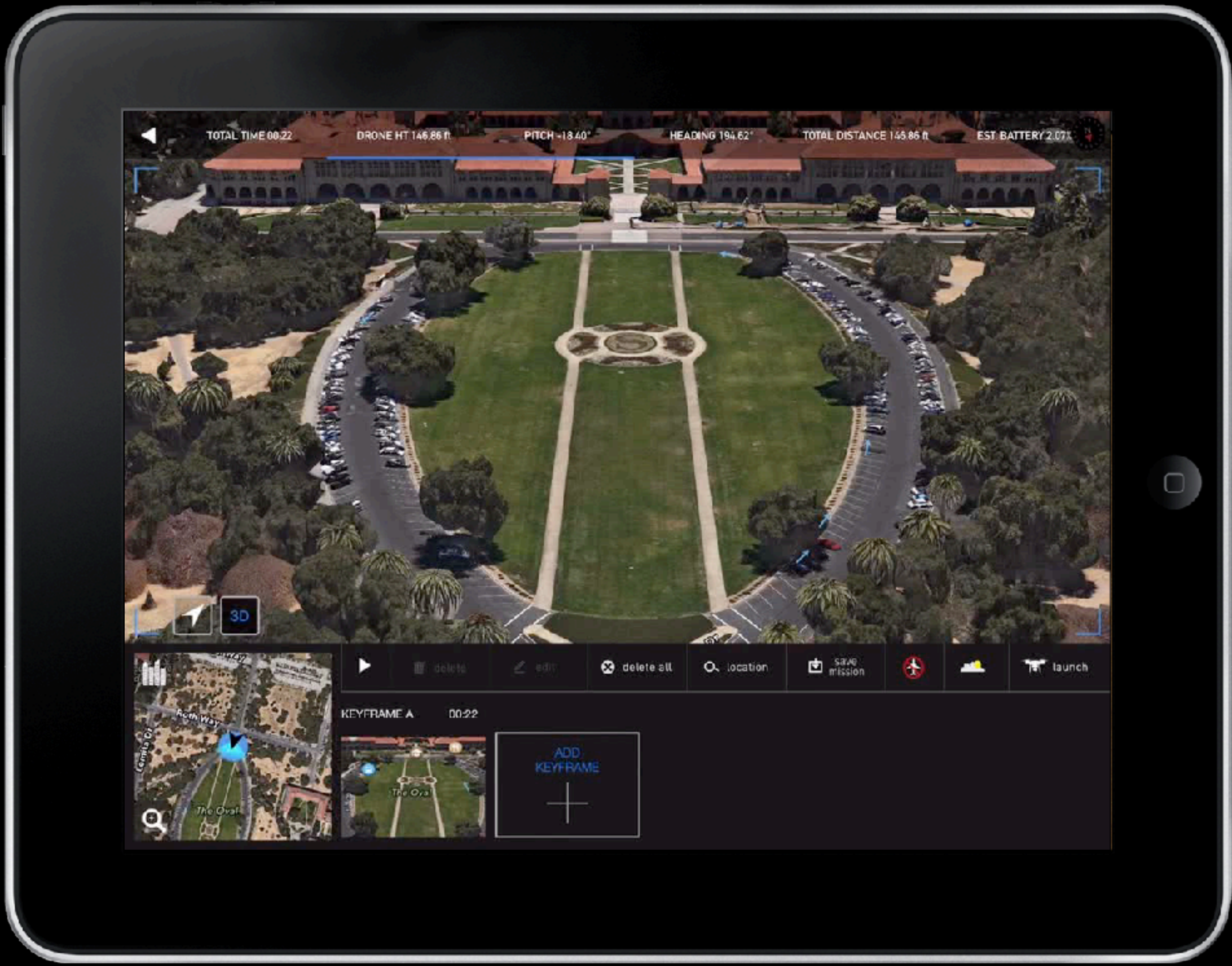
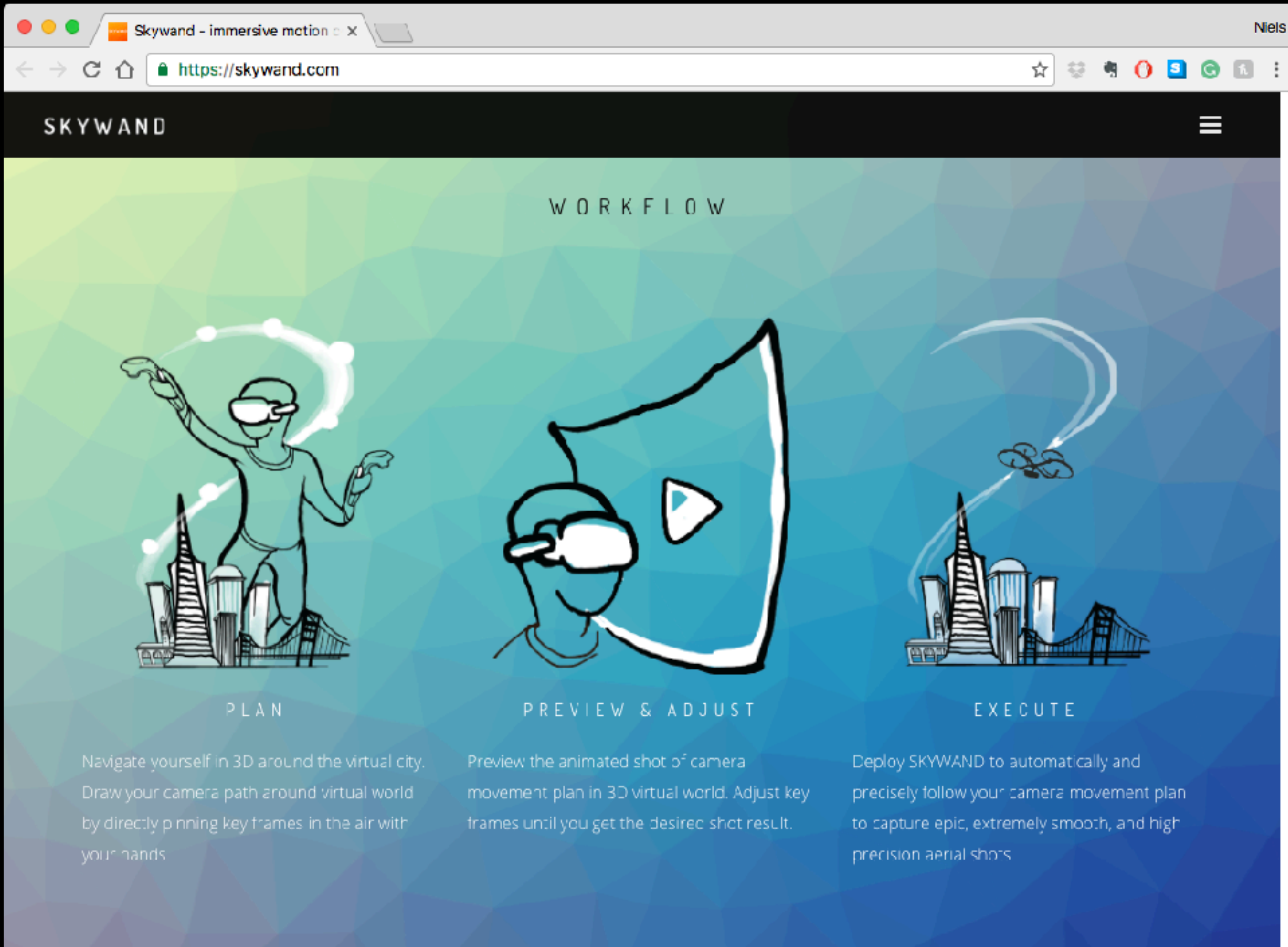
Developer Website
© 2016 FreeSkies Inc.
Description
FreeSkies CoPilot is the best way to capture aerial videos and photos easily and safely. Create unique, creative, and dynamic videos in a simple to use, 3D interface. You don't need to be an expert drone pilot to capture exciting visuals. You focus on the photography, and CoPilot handles the rest. IMPORTANT: Apple Maps 3D data is currently limited, please check your area before purchasing.
...
more


TOTAL TIME 00:22
DRONE HT 146.86 ft
PITCH -18.40°
HEADING 194.62°
TOTAL DISTANCE 145.86 ft
EST BATTERY 2.07%
3D
delete
edit
delete all
location
save mission
launch
KEYFRAME A
00:22
ADD KEYFRAME
Roth Way
The Oval


Skywand - immersive motion
Niels
https://skywand.com
SKYWAND
WORKFLOW
PLAN
Navigate yourself in 3D around the virtual city. Draw your camera path around virtual world by directly pinning key frames in the air with your hands
PREVIEW & ADJUST
Preview the animated shot of camera movement plan in 3D virtual world. Adjust key frames until you get the desired shot result.
EXECUTE
Deploy SKYWAND to automatically and precisely follow your camera movement plan to capture epic, extremely smooth, and high precision aerial shots


SKYWAND
Create keyframes by pressing trigger button

Real footage

Flight plan

SKYWAND

FEELINGS

THANK YOU

Pat
Committee - Stu, Dave, Juan, Maneesh, Mac
Collaborators - Mike R, Jane E, Anh T, Dan G, James L, Zach D, Juan A, Eric D, Andrew K, Sebatian B, Alex A, ….
Industry Partners - All the 3DR folks, Swift Nav folks, Adobe folks, DJI
User Study Participants
Stanford UAV Club & Drone Cinematography community - Trent, Eli, Eric C, George K,…
Students - Anh, Harrison, Vicky, Eli, Kat, Stephanie, Noa, Jorge
Fellow Inmates & Colleagues in the Graphics lab, Stanford, Pixar, Yahoo, …
Burning Man families the Dusty Connection, the Shady Waffle, Monks of Funk
Friends off the Farm Gleb, Ashley, Marcello, Yizhuo, Patrick, Trisha, Eric, Trent, Fergus, Carrie, Sher, Jennifer, Hendrik in SA, …
EECS House @ Cal
Mentors - Henry Chamberlain, Annelie Starke, Lona Antoniadis, so many more
Silicon Graphics branch, South Africa - Neil McGowen, …
Extended Family - Ackermans, Du Toits, Oosthuizens, Jouberts, …
Girlfriend Liz, who lives life so well that Death will tremble to take her

THANK YOU

Mental Health

FLORAINE BERTHOUZOZ
1984-2015

NELLIS OOSTHUIZEN
1929-2016

A VISION OF THE FUTURE

"The Universe is made of Stories, not of Atoms"
- Muriel Rukeyser

Robotic systems that intelligently balance
Human Interfaces, Aesthetic and Technical Knowledge

will enable capturing your stories, while remaining immersed in your experience.

THANK YOU