SCUOLA DI DOTTORATO IN SCIENZE MISURE E
TECNOLOGIE PER L'INGEGNERIA E LO SPAZIO

DESIGN OF A ROBOTIC ARM FOR LABORATORY SIMULATIONS OF SPACECRAFT PROXIMITY NAVIGATION AND DOCKING

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SUPERVISORE: **Alessandro Francesconi**

Outline of the Presentation

- MOTIVATION AND OBJECTIVES
- STATE OF THE ART
- WHAT'S NEW
- APPLICATIONS
- WBS
- CURRENT PROGRESS

INTRODUCTION

- THE INCREASING NUMBER OF ORBITING OBJECTS HAS LAID THE NEED FOR SERVICING AND MAINTENANCE OPERATIONS (OSS)
- THE GOAL OF THIS RESEARCH IS THE DEVELOPMENT OF A MANIPULATOR ARM FOR GROUND TESTING OF OOS OPERATIONS
- OOS OPERATIONS CONSIST MAINLY OF:
  - RENDEZ-VOUS
  - DOCKING
  - BERTHING

STATE OF THE ART

- DLR's EPOS EXPERIMENT IS ONE OF THE LEADING EDGE OOS SIMULATION FACILITY
- TWO 6DOF INDUSTRIAL ROBOTS AND A 25 M LONG TESTING SITE
- THE HARDWARE-IN-THE-LOOP SYSTEM ALLOWS THE SIMULATION OF **DYNAMIC CONTACTS, GRAVITY AND EVEN SUNLIGHT ILLUMINATION**
- THE CONTROLLER IMPOSES A DYNAMICS THAT IS DIFFERENT FROM THE LABORATORY DYNAMICS, WHICH IS CONTINUOUSLY CORRECTED

WHAT'S NEW

- THIS PROJECT PROPOSES AN ALTERNATIVE TO THESE HUGE AND COSTLY FACILITIES
- THE SYSTEM WILL BE CONSTITUTED BY A SINGLE ROBOT WITH THE FOLLOWING PECULIARITIES:
    - THE CONTROLLER COMPUTES AND IMPOSES THE REAL-TIME ORBITAL TRAJECTORY, AND IMPOSES A DYNAMICS THAT IS DIFFERENT FROM THE LABORATORY DYNAMICS
    - ACTIVE CONTROL OF THE TRAJECTORY WITH FORCE TRANSDUCERS
    - POSSIBILITY TO SIMULATE MUCH BIGGER SCENARIOS THAN THE MERE WORKSPACE WITH THE AID OF DYNAMIC SCALING LAWS
    - MUCH SMALLER DIMENSIONS AND WEIGHT

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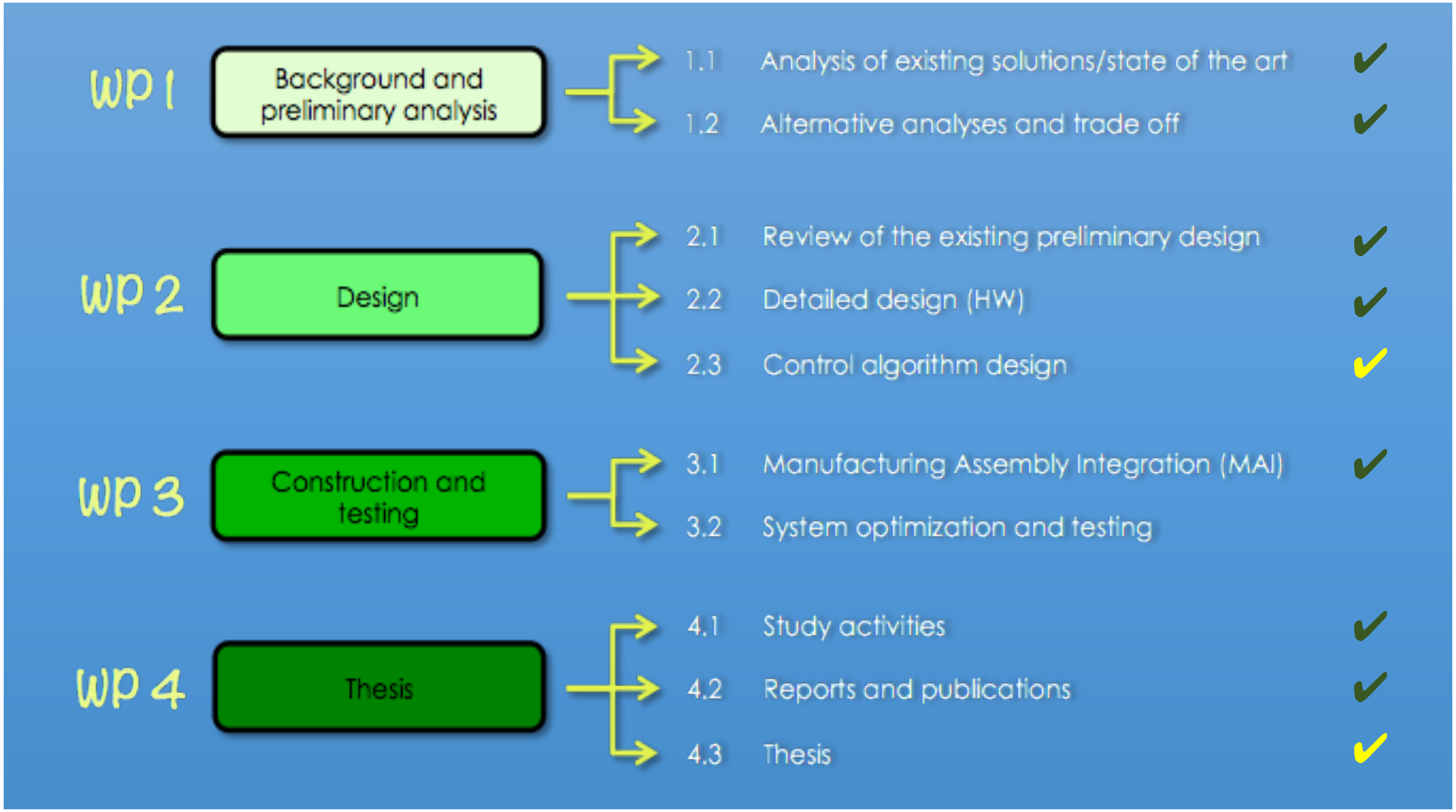
WORK BREAKDOWN STRUCTURE



WHAT'S NEW

- THE WORK DONE UP TO NOW WILL BE PRESENTED AS BROKEN DOWN IN THE FOLLOWING SECTIONS:

A) MECHANICAL DESIGN (PD)

B) SIMULATION SCENARIO DESIGN

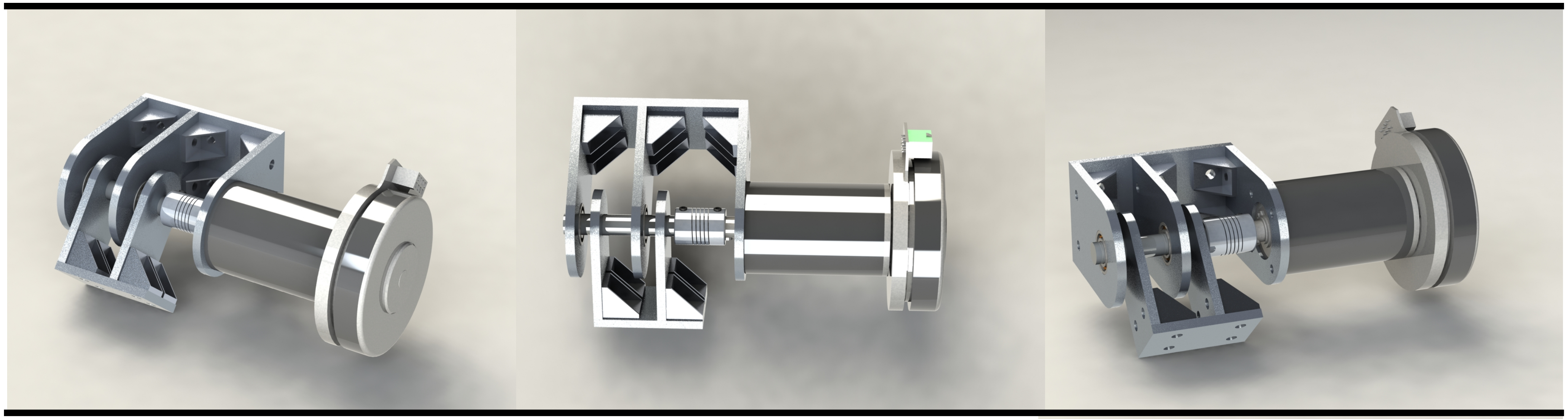
C) SENSOR SUITE DESIGN

INTERNATIONAL COLLABORATIONS

- BOSTON UNIVERSITY
- MIT
- GEORGIA INST. OF TECHNOLOGY

MECHANICAL DESIGN

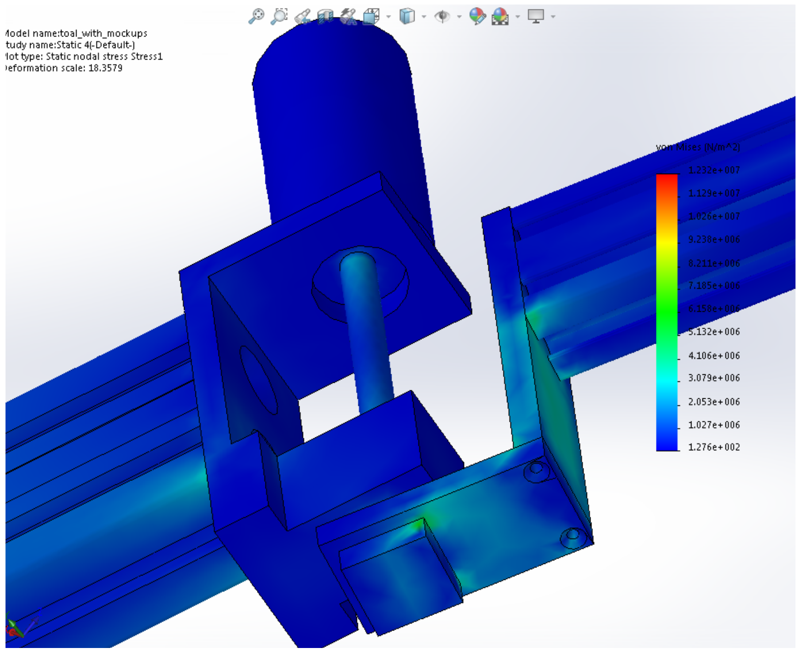
- FOLLOWING THE PRELIMINARY DESIGN AND REQUIREMENTS VERIFICATION (COMPLETED IN THE FIRST YEAR), STARTING FROM JANUARY 2015, I SUPERVISED A MASTER STUDENT FOR THE FINAL SELECTION OF THE MOTORS AND GEARINGS, WHICH LED IN SEPTEMBER 2015 TO THE WRITING OF A MASTER THESIS THAT CONTAINED THE COMMERCIAL PARTS TO BE PURCHASED FOR THE FACILITY.

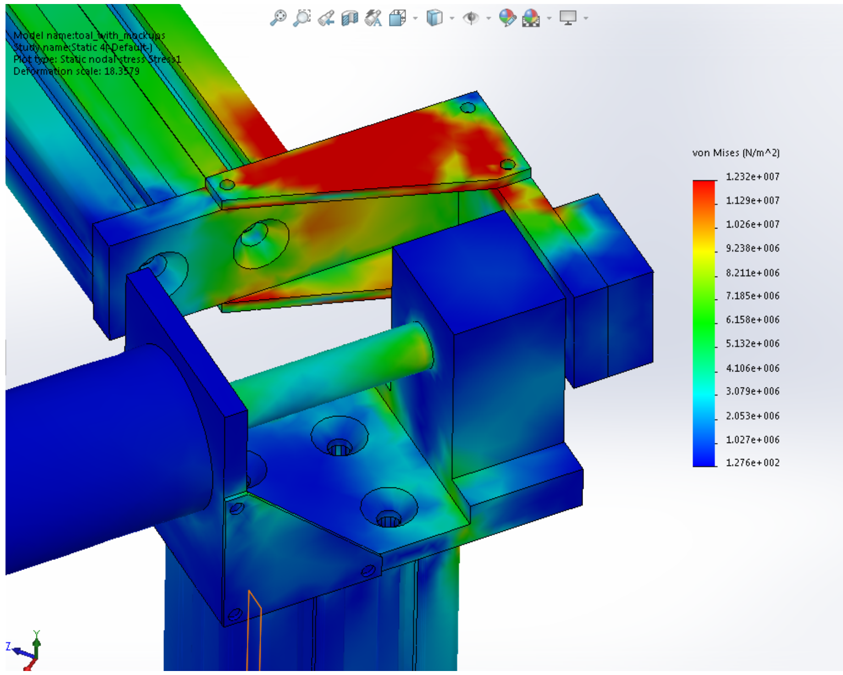


preliminary design

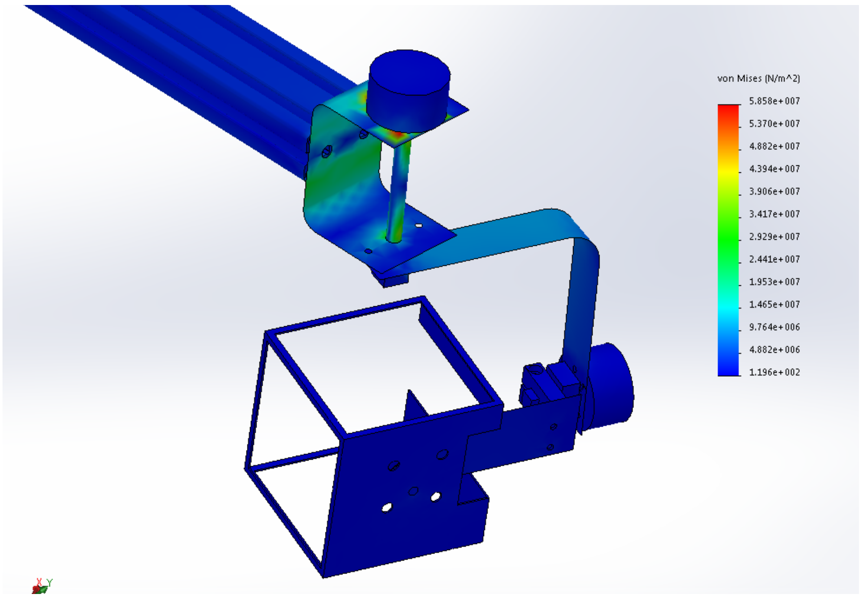
MECHANICAL DESIGN

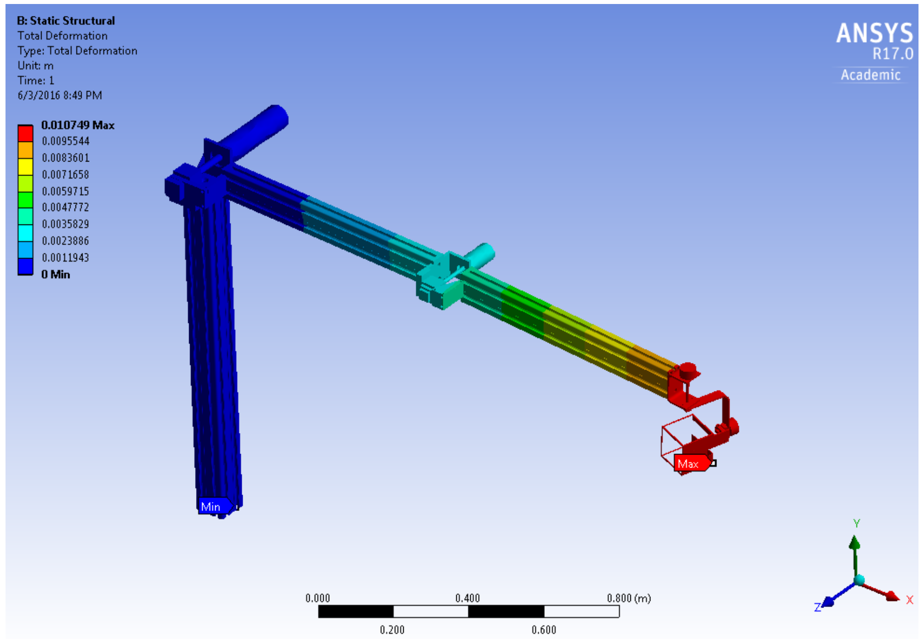
- ONCE A FIRST DRAFT OF THE JOINT BLOCKS WAS COMPLETED, I PROCEEDED WITH THE FEM SIMULATIONS TO VERIFY THE CHARACTERISTICS OF THE SYSTEM.
- I STARTED FROM A STATIC SIMULATION CAMPAIGN WHICH LED TO THE CORRECT SIZING OF THE COMPONENTS IN ORDER TO AVOID OVER-ENGINEERING.

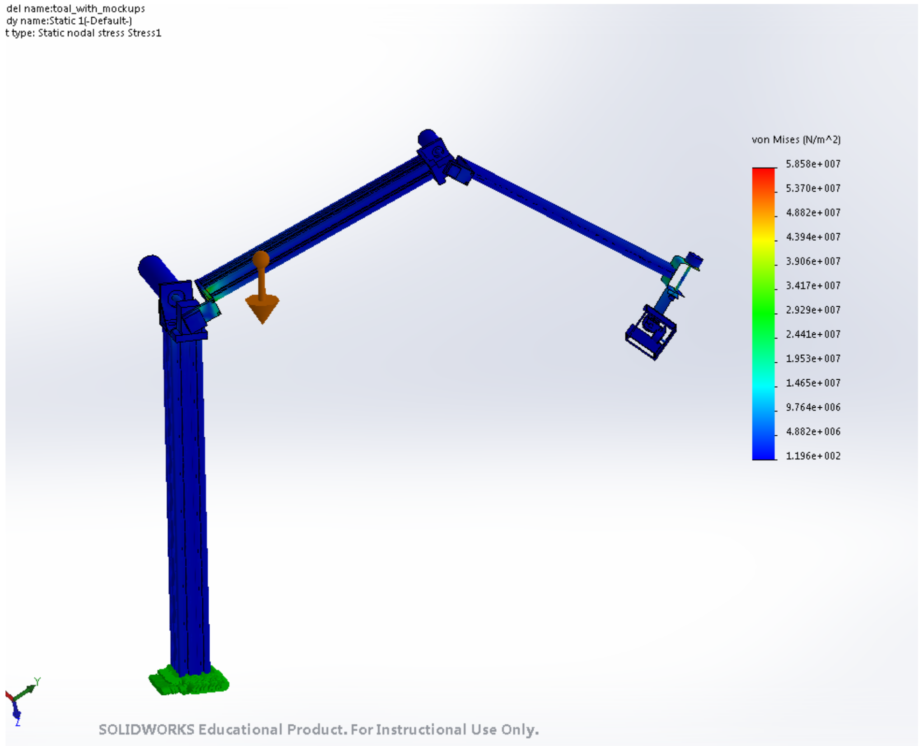


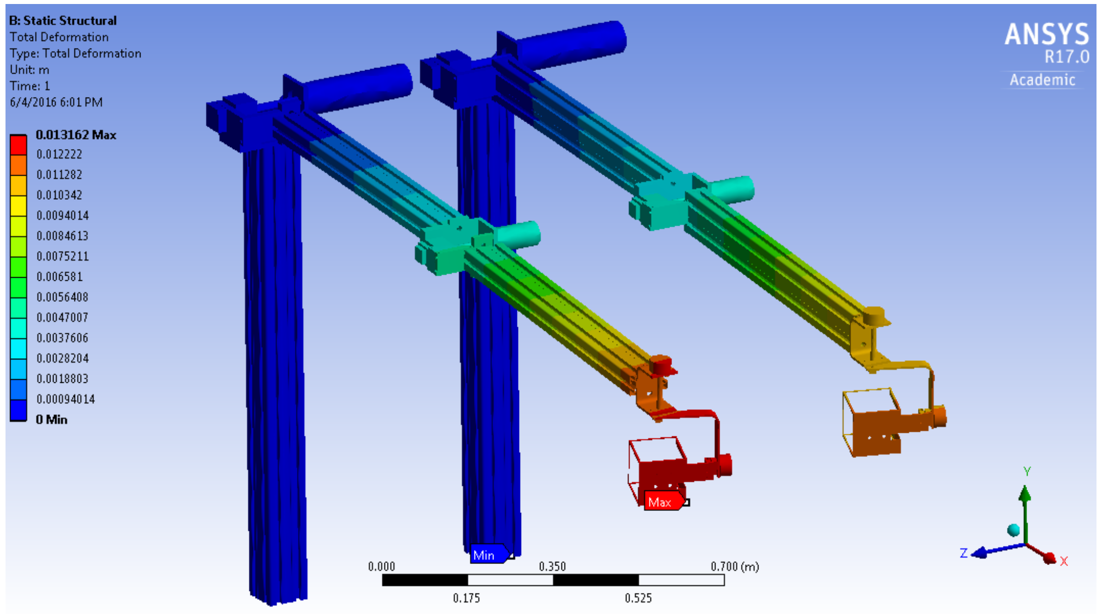


MECHANICAL DESIGN



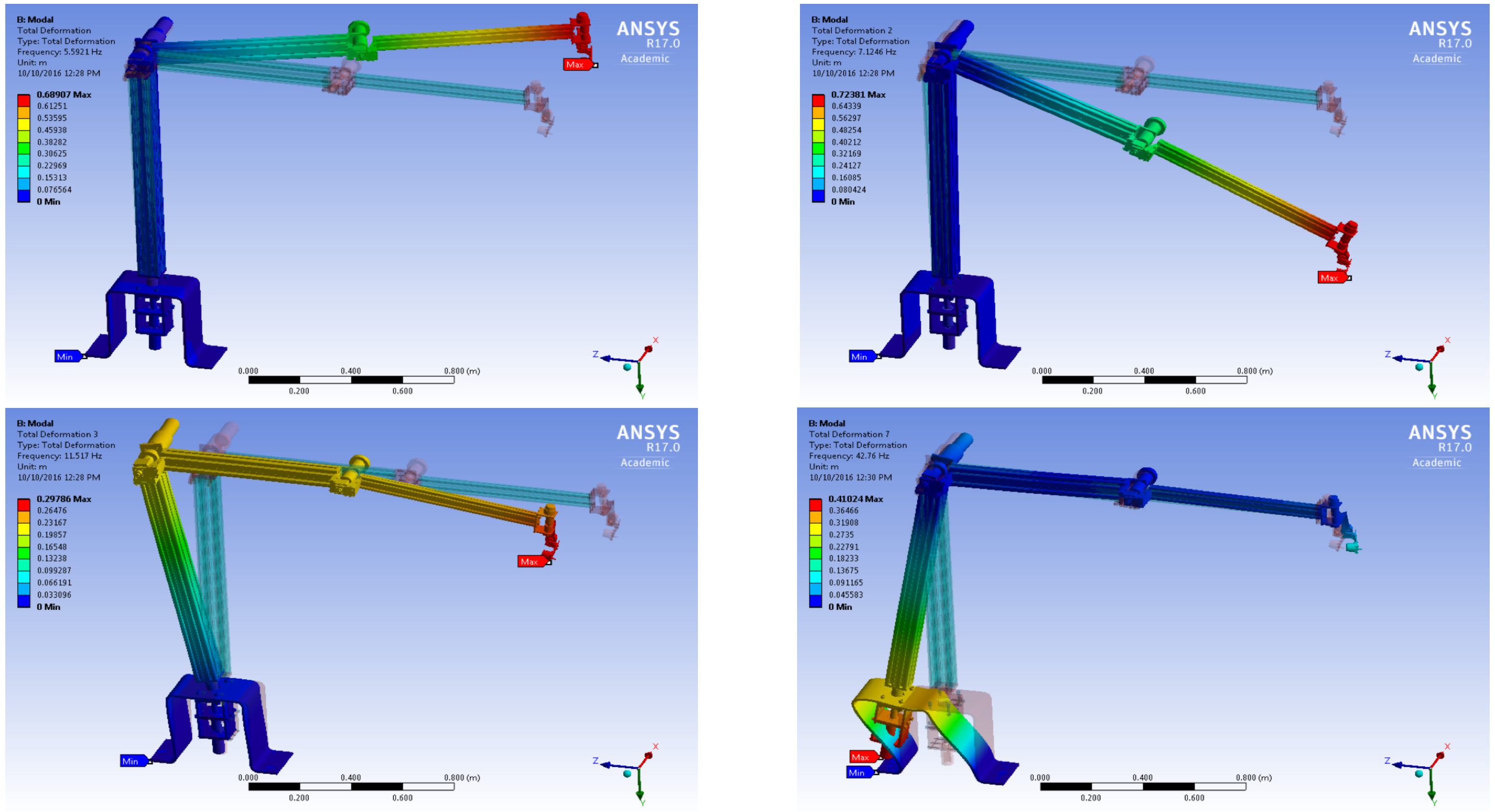






MECHANICAL DESIGN

- FINALLY, A MODAL ANALYSIS WAS PERFORMED AND LED TO THE CALCULATION OF THE VIBRATIONAL FREQUENCIES OF THE SYSTEM.
- THIS LED TO A FURTHER REFINEMENT OF THE DESIGN, BY CHANGING THE THICKNESS OF SOME OF THE SUPPORTING PLATES AND BY ADDING STRENGHETING TRIANGLES AT JOINT 2 AND 3.



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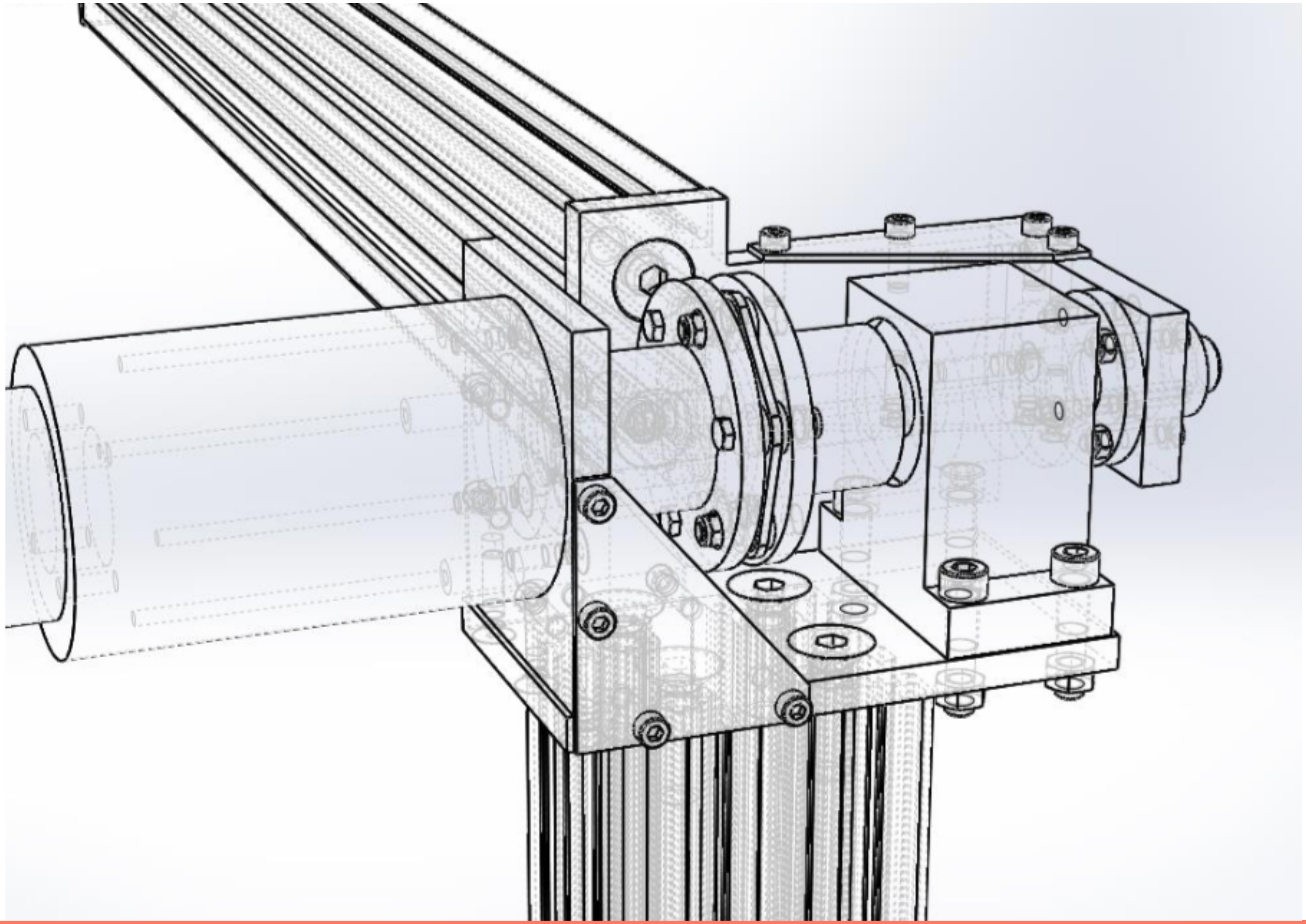

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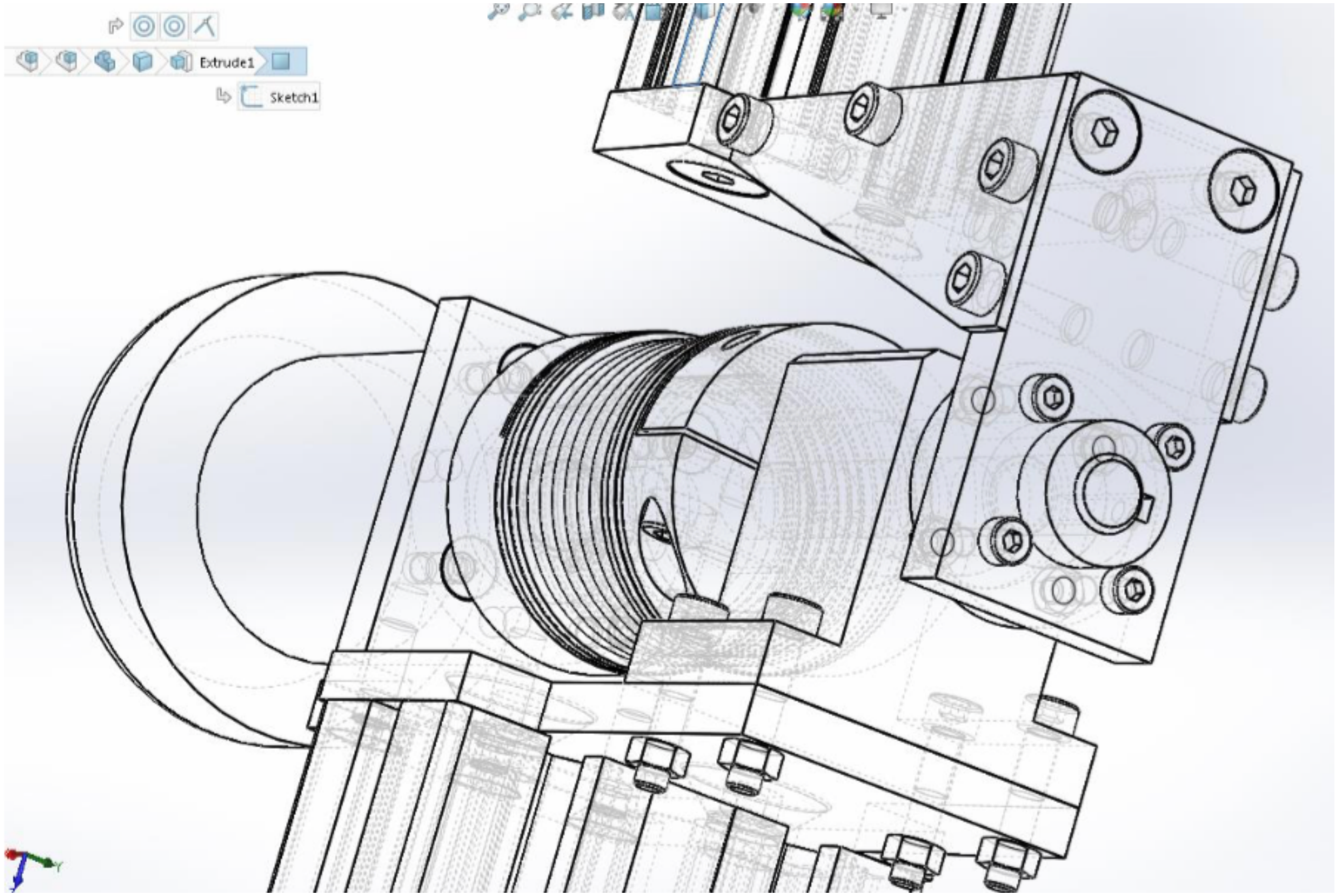

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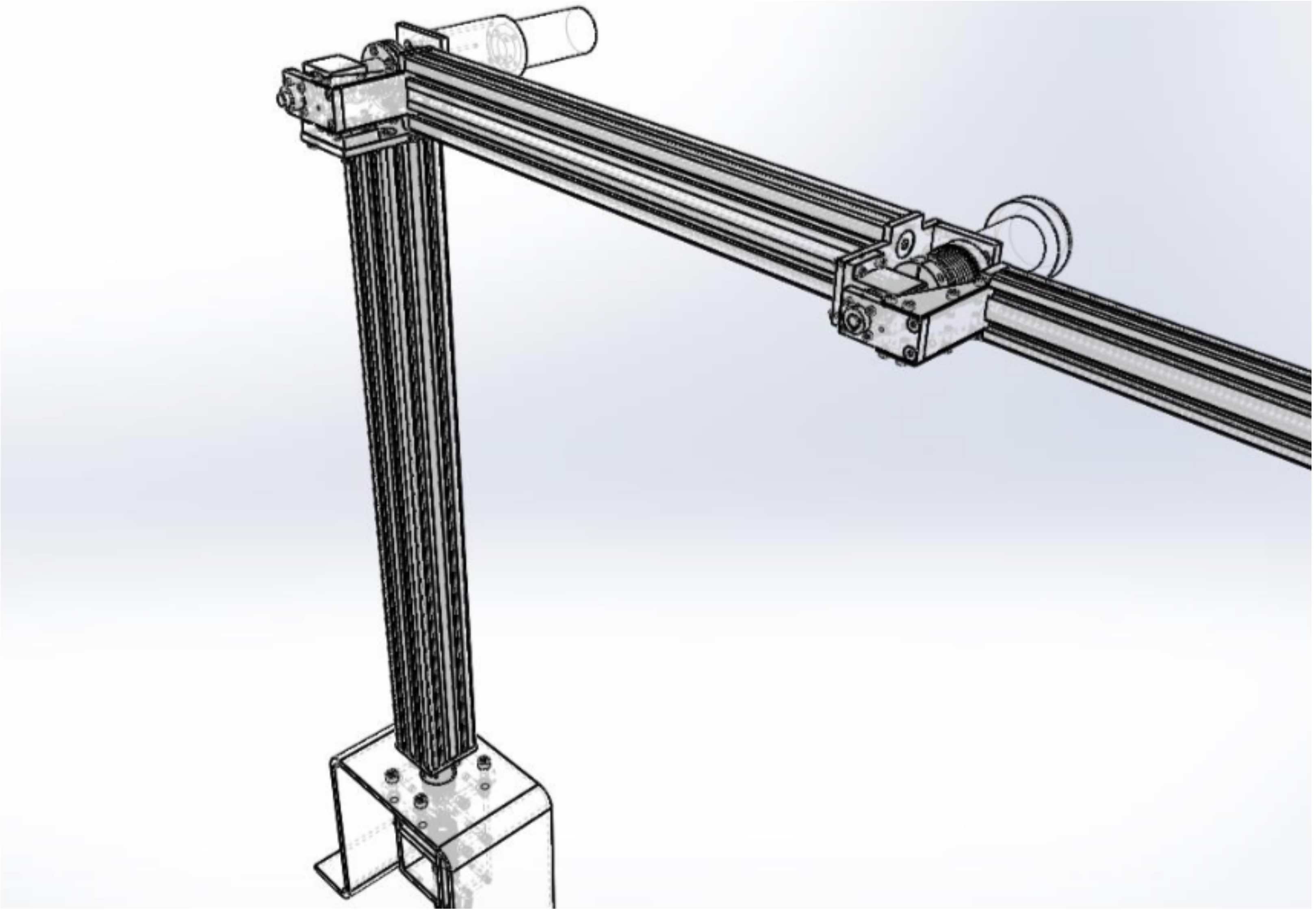

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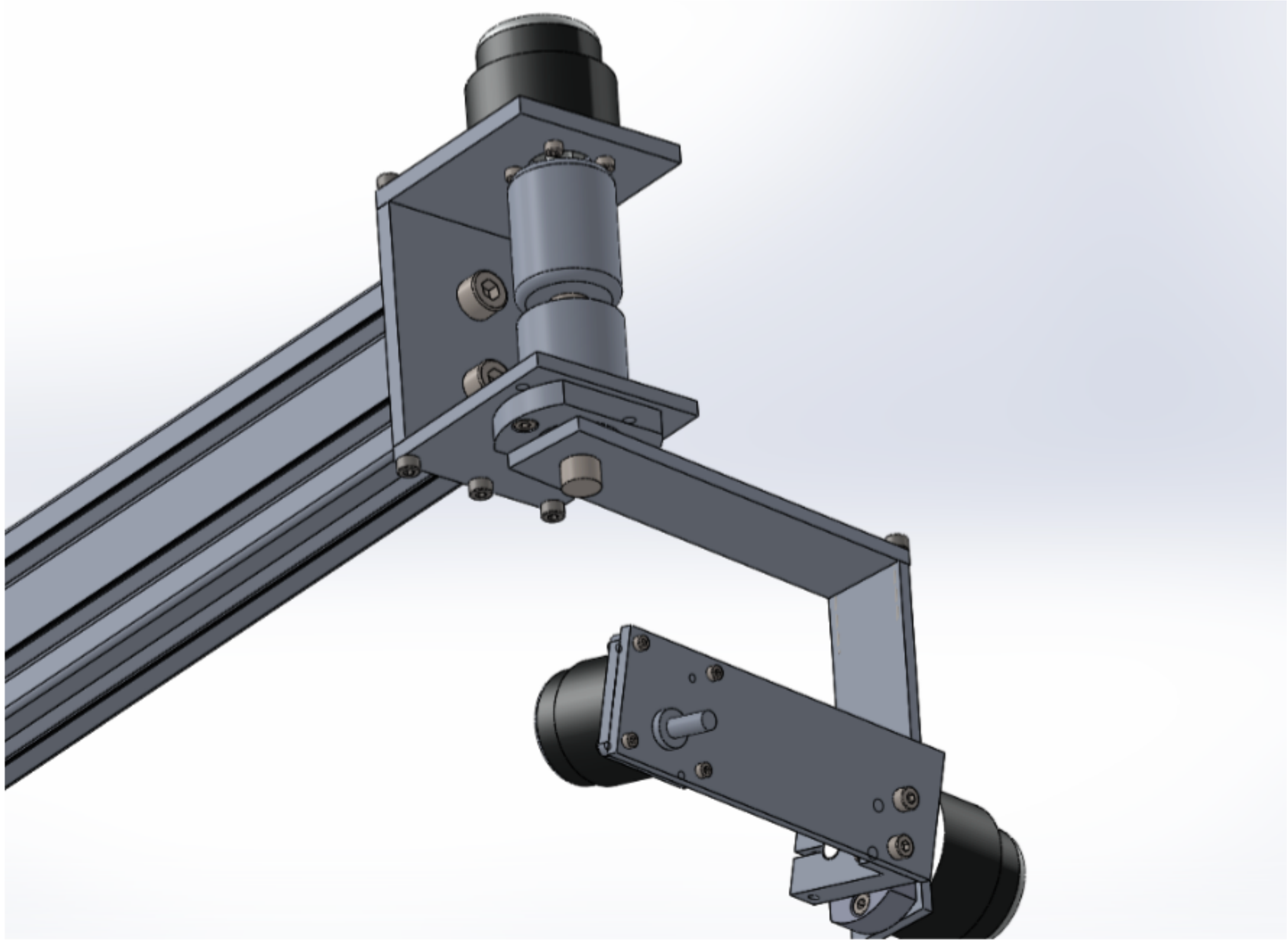

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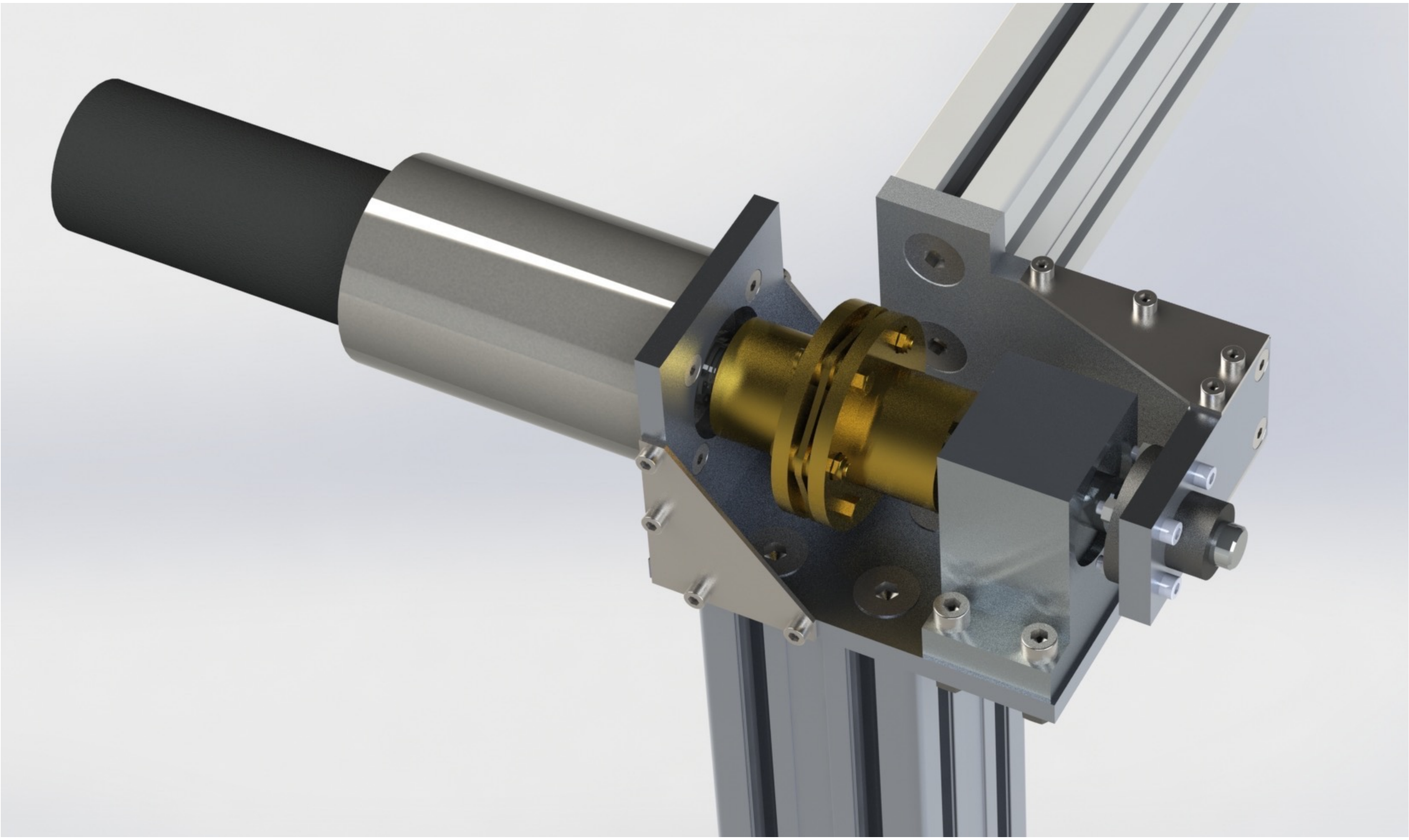

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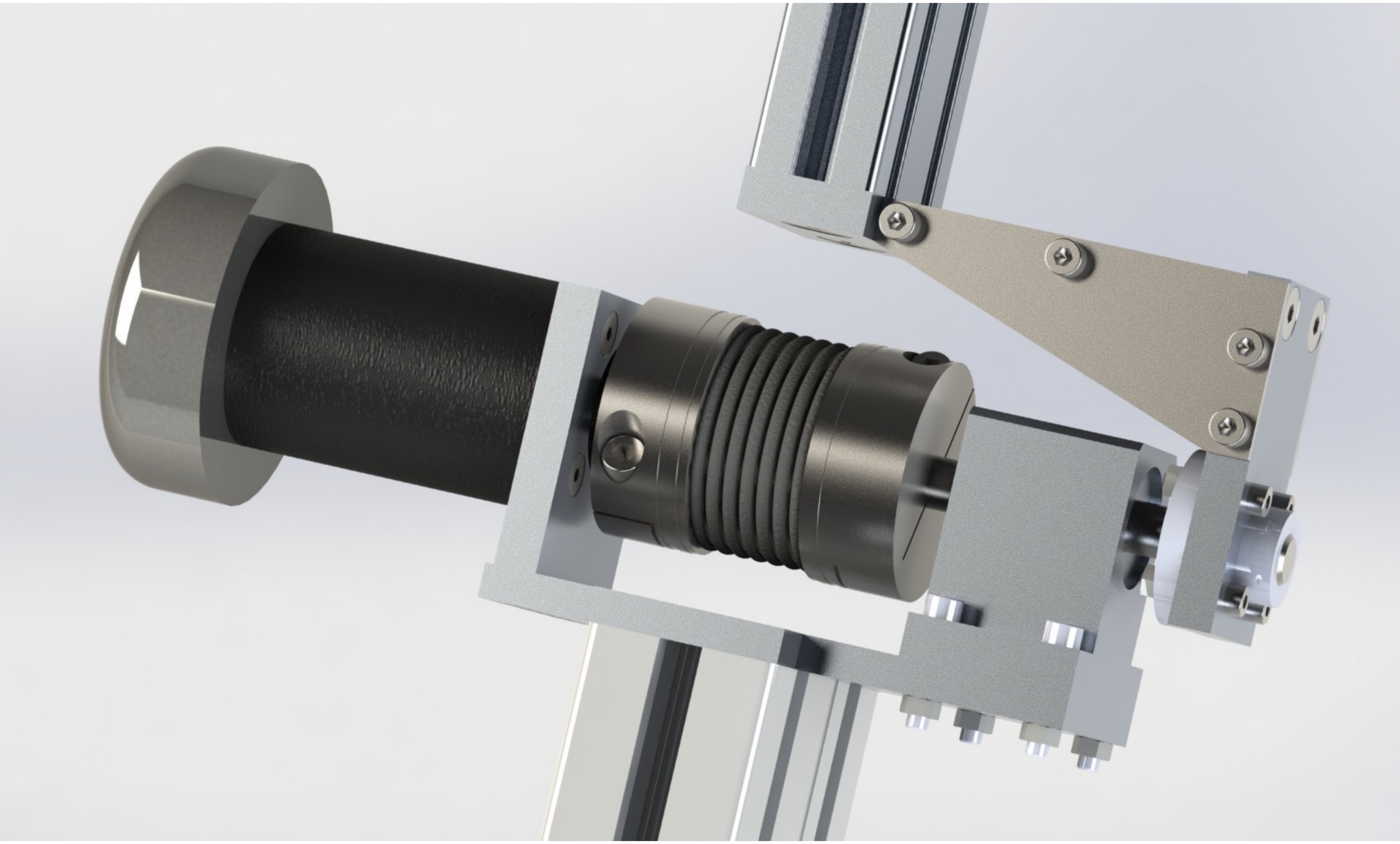

MAIT - Manufacturing & Assembly

- As of October 2016, most of the parts to be assembled have been procured. Assembly has started and is expected to be finished in the first weeks of November

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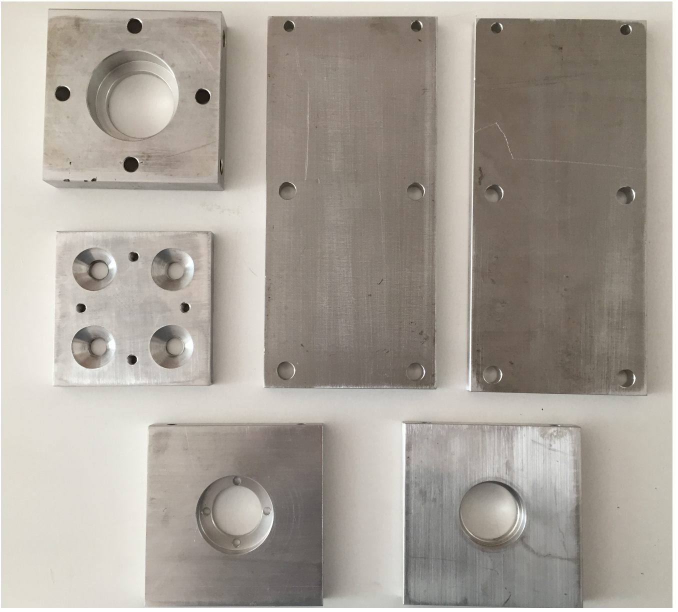

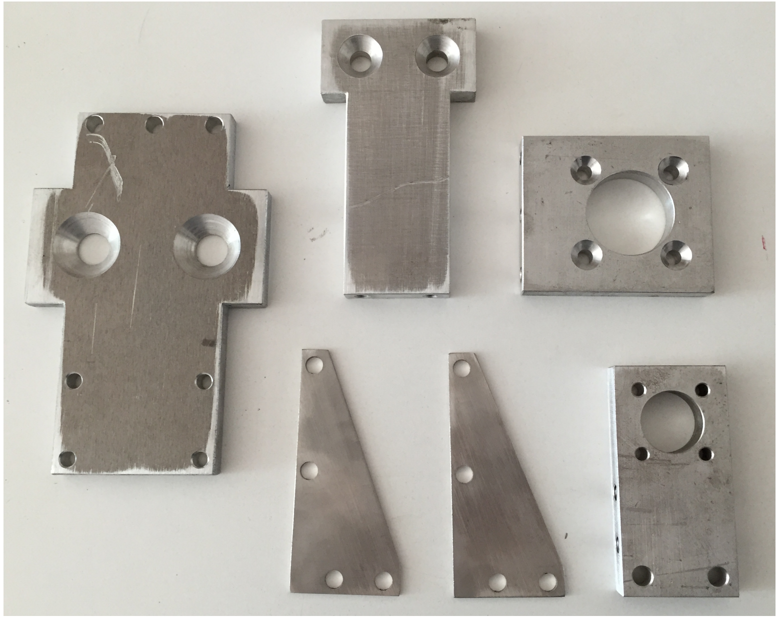

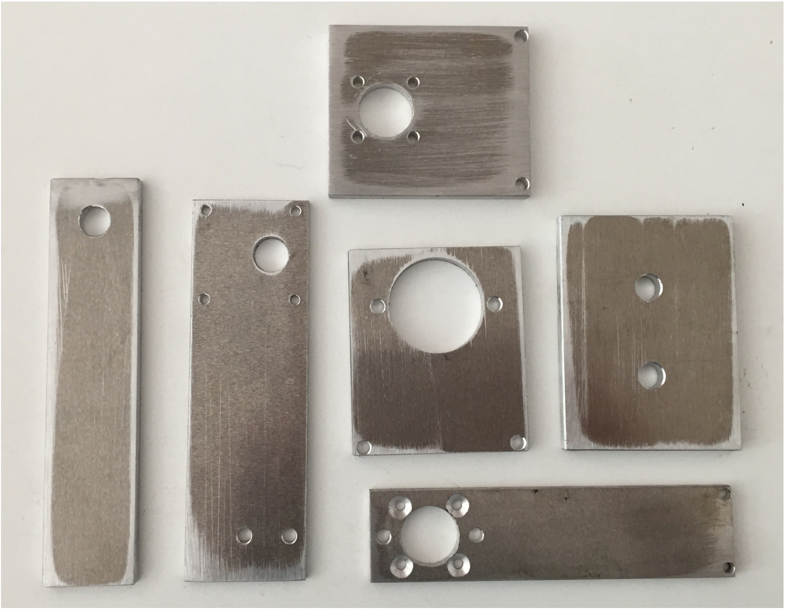

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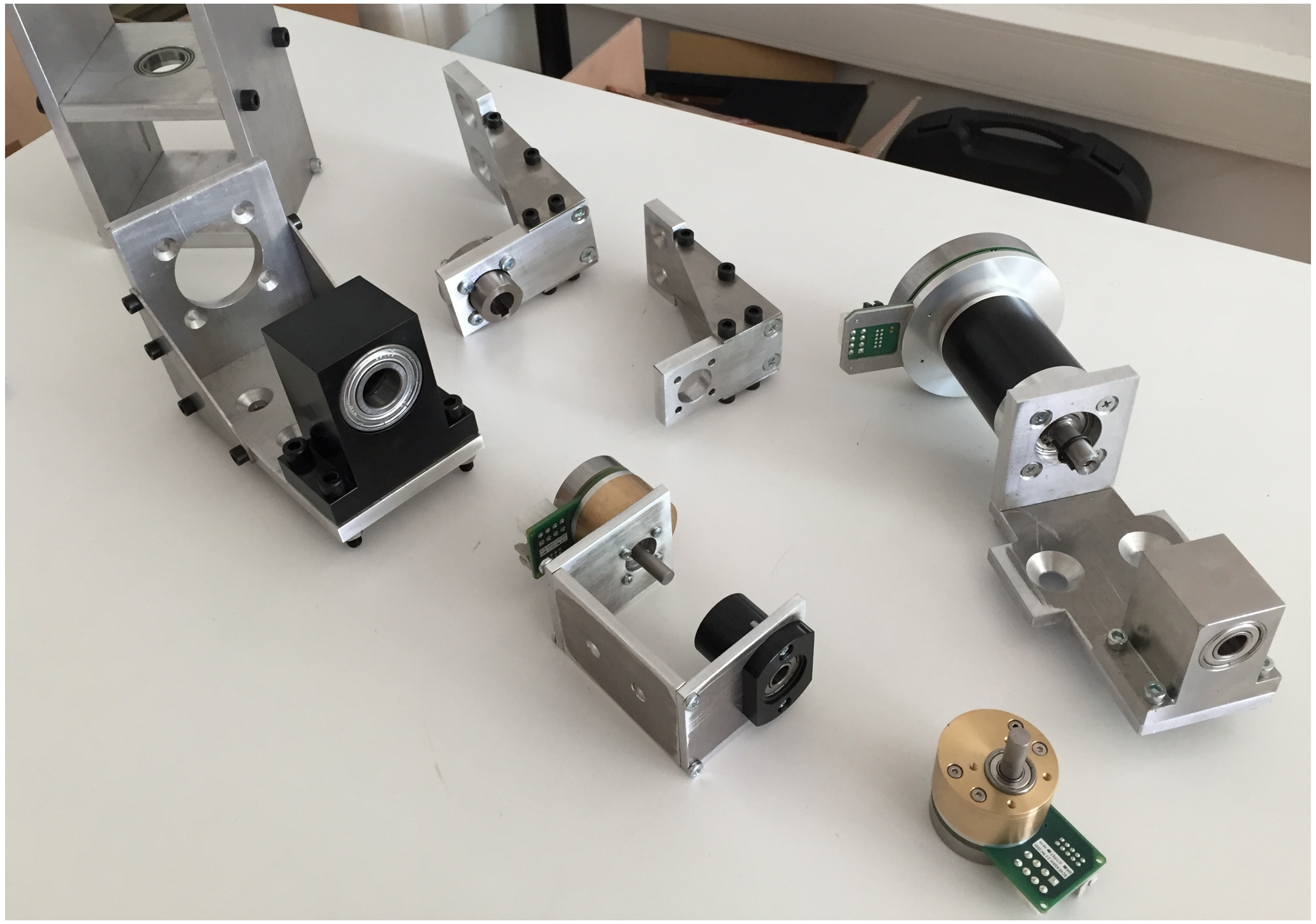
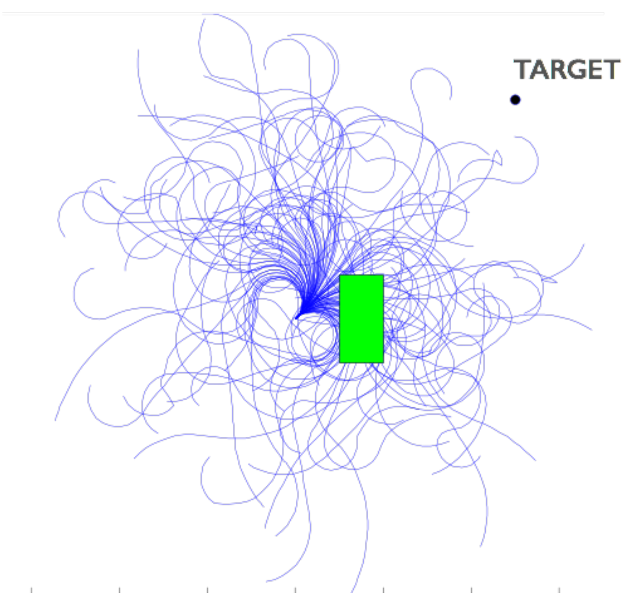


CROSS ENTROPY TRAJECTORY PLANNING

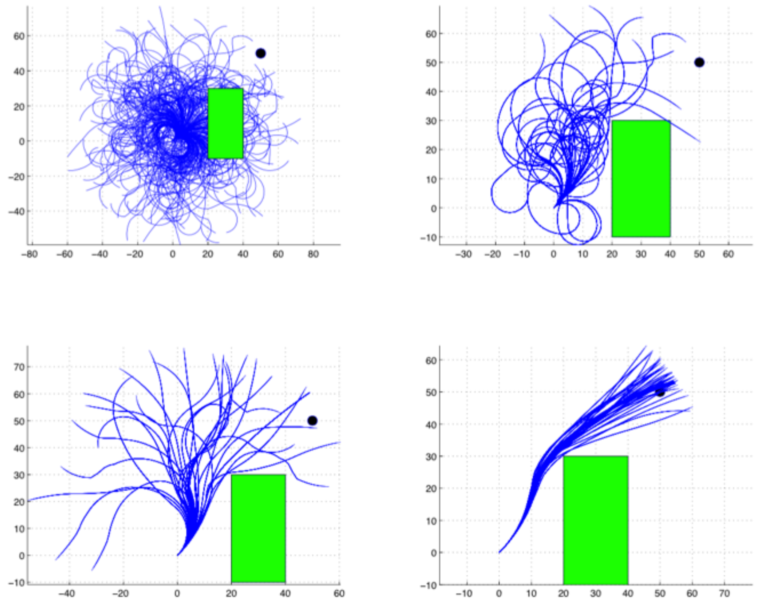
- LOOKING AT SIMULATION SCENARIOS FOR THE ROBOTIC FACILITY, I WORKED ON CROSS-ENTROPY BASE SLAM TECHNIQUES UNDER THE SUPERVISION OF PROF. P. TSIOTRAS FROM GEORGIATECH UNIVERSITY (ATLANTA, USA)

- CROSS ENTROPY STRATEGIES ARE A STOCHASTIC WAY TO PERFORM SLAM MINIMIZING, THROUGH STATISTICAL TOOLS, THE COMPUTATION AND ACTUATION COSTS.

MONTECARLO



CROSS ENTROPY (4 iterations)



CIS*S G. COLOMBO

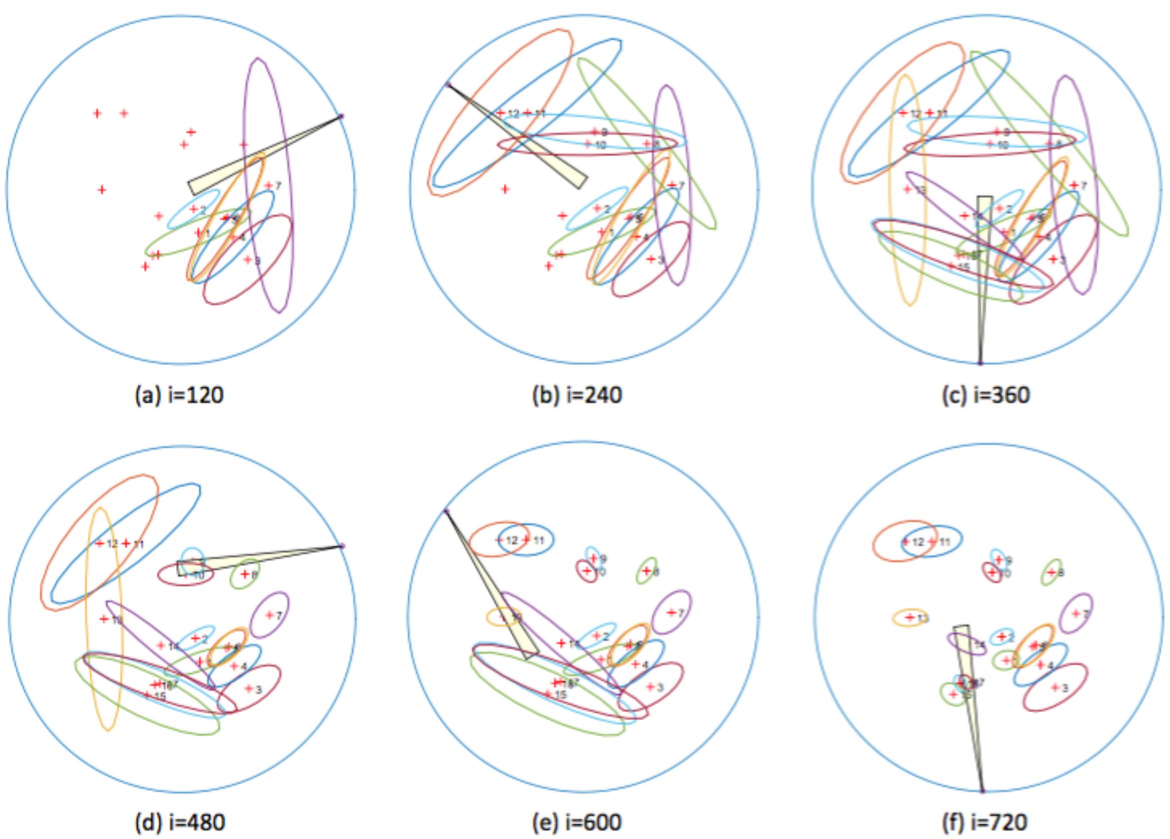
CROSS ENTROPY TRAJECTORY PLANNING

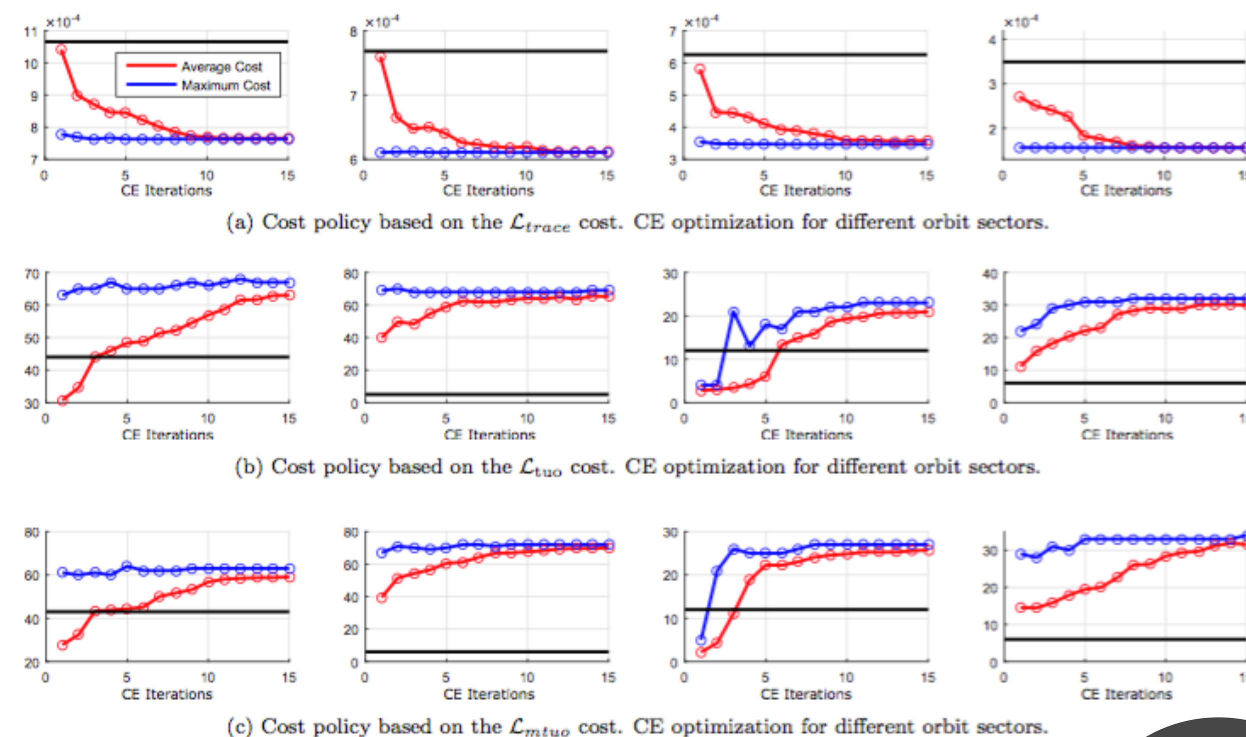
- NOVELTY: EXISTING WORK IN PROXIMITY OPERATIONS SOLVE THE PROBLEM OF CONTROL AND ESTIMATION **INDEPENDENTLY**
- WE INTEGRATE STOCHASTIC OPTIMIZATION WITH AGENT LOCALIZATION TO THE PROBLEM OF A CHASER CIRCUMNAVIGATING A TARGET. THE GOAL IS TO LOCALIZE SOME LANDMARKS LOCATED ON THE TARGET SATELLITE.
- GOAL IS TO MINIMIZE A COST FUNCTION THAT ENCLOSES BOTH THE FINAL UNCERTAINTY OF THE ESTIMATE AND THE ACTUATION COST:

$$\mathscr{L}(\mathbf{x},\mathbf{u}) = \|e^2(t_N)\| + \int_0^{t_N} \left(Q(\mathbf{x}) + \frac{1}{2}\mathbf{u}^T R\mathbf{u} \right) \mathrm{d}t$$

CROSS ENTROPY TRAJECTORY PLANNING

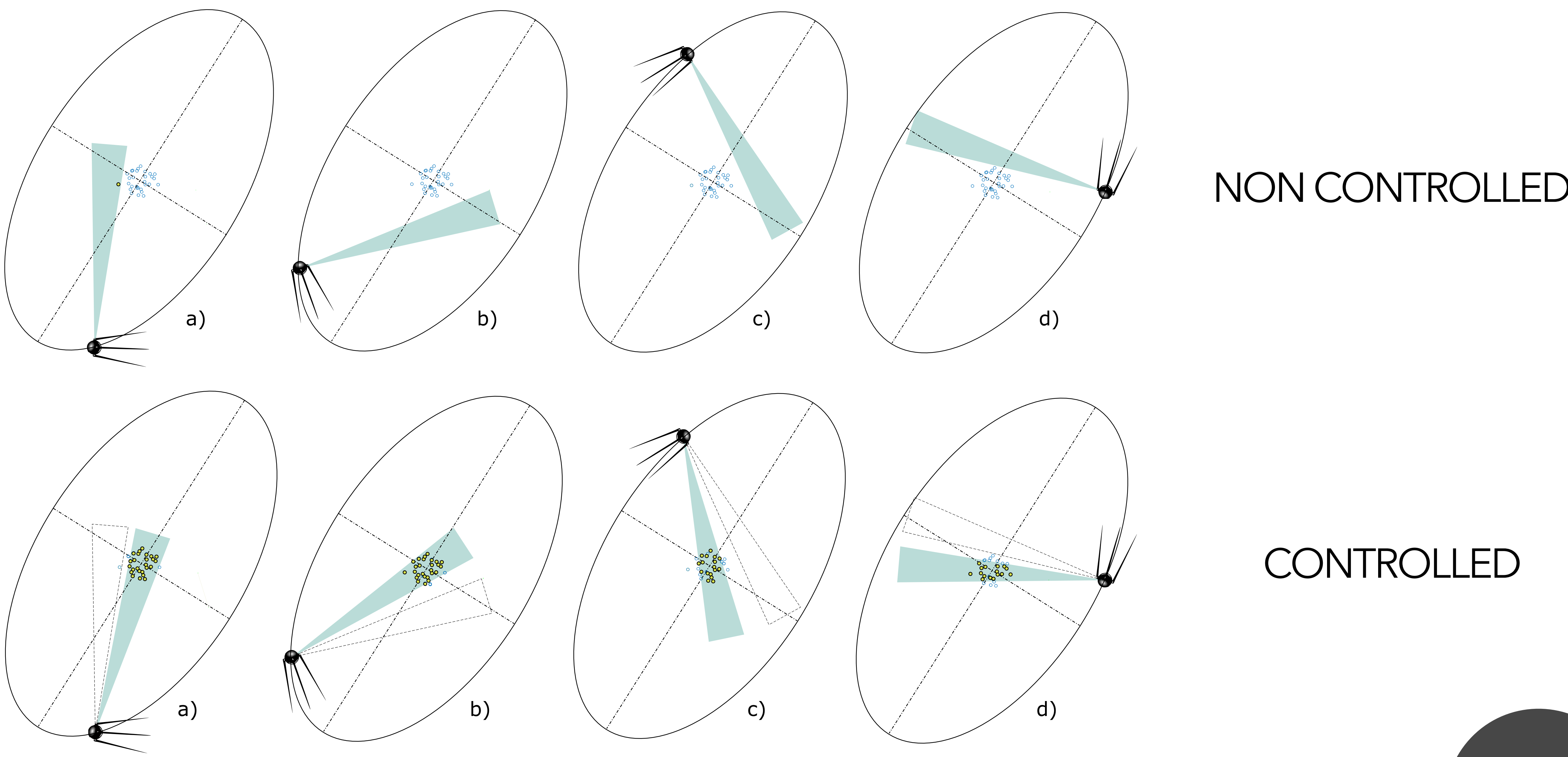
- TWO PUBLICATIONS WERE PRODUCED BY APPLYING THIS STRATEGY TO THE SCENARIO OF CONTROLLING A CAMERA MOUNTED ON A SATELLITE CIRCUMNAVIGATING A TARGET, PERFORMING SLAM
- SEVERAL CONTROL POLICIES WERE PERFORMED AND A FULLY 3D SIMULATION WITH A CLOHESSY-WILTSHIRE FRAME WAS USED





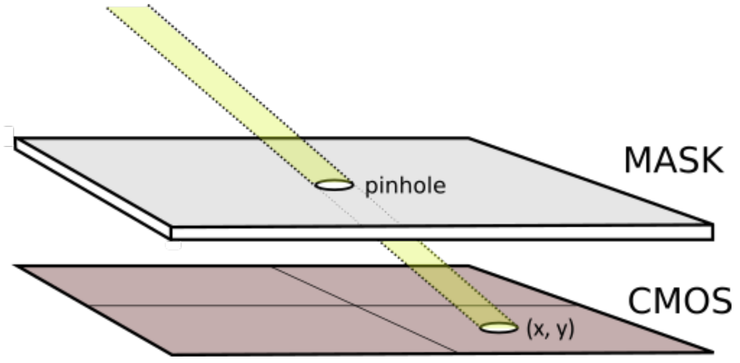
CROSS ENTROPY TRAJECTORY PLANNING

- THIS NEW TECHNIQUE OUTPERFORMED BOTH THE NON CONTROLLED CASE AND A PD CONTROLLER



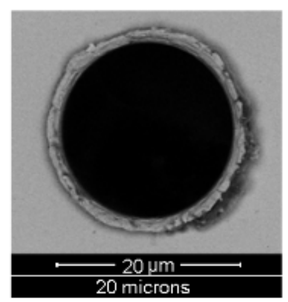
SUN SENSOR

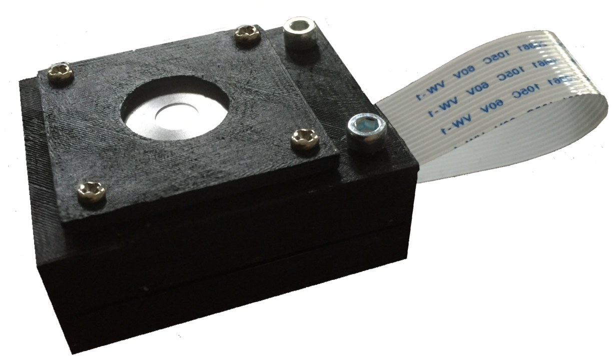
- AS A SPINOFF FROM THE STUDENT PROJECT ONORBIT, I DEVELOPED A SUN SENSOR THAT WILL SERVE AS AN ATTITUDE SENSOR MOUNTED IN THE SATELLITE MOCKUP AT THE TIP OF THE ROBOT END EFFECTOR.
- AS OF TODAY, THERE EXIST SEVERAL PRIVATE COMPANIES THAT OFFER SENSORS WHICH HAVE A MAXIMUM ACCURACY OF 0.3-0.5° AND PRICES STARTING AT $3000/UNIT
- WE USED OFF THE SHELF, ACTIVE PIXEL SENSOR (CMOS) COMPONENTS WITH HIGH RESOLUTION AND LIMITED FOOTPRINT.
- THE SIMPLIFIED WORKING PRINCIPLE IS BASED ON THE PINHOLE CAMERA



SUN SENSOR

- A PROTOTYPE OF THE SENSOR HAS BEEN CREATED USING OFF THE SHELF COMPONENTS:
  - A CMOS CAMERA, A 20UM PINHOLE MASK & A 3D PRINTED ENCLOSURE WITH DIMENSIONS 28X30X15 MM



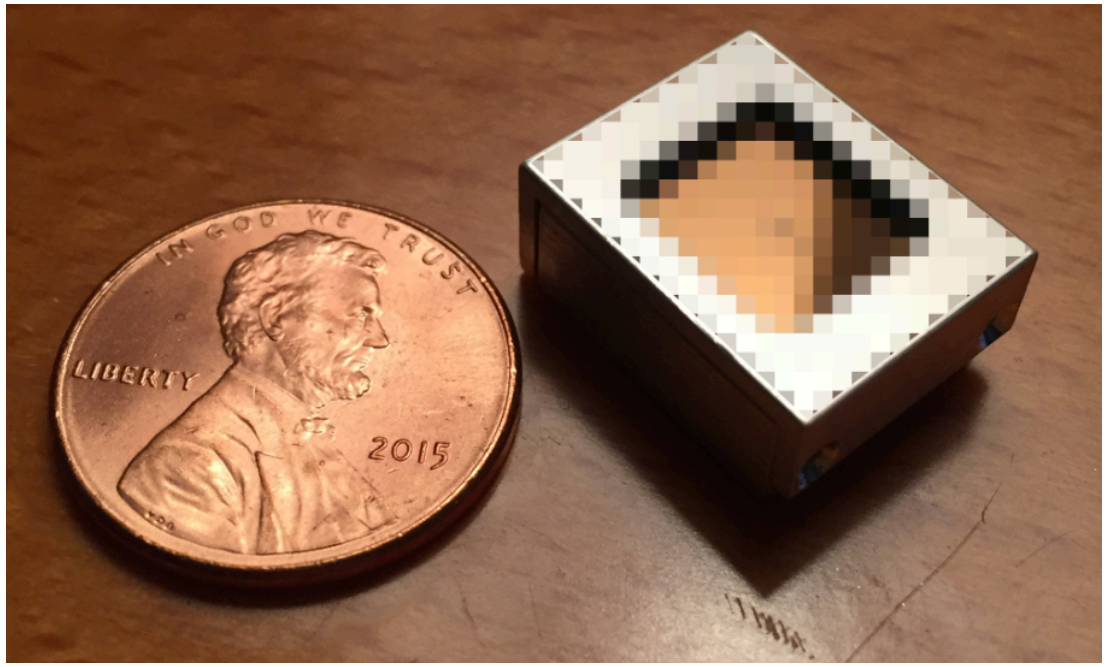


- TOTAL MASS IS 15 GRAMS AND THE SIZE IS 28X30X15 MM.

FIELD OF VIEW	ACCURACY	RESOLUTION	PRECISION	COST
66.2 x 51.1°	±0.02°	±0.023°	±0.024°	<$35

Sun Sensor

- Starting from the current prototype, we refined the sensor architecure and miniaturized the final product: the new sensor weighs only 2.5 grams and has a dimensions sum of 35 mm, making it the **smallest** Sun sensor on Earth in 2016 with these performances



CONCLUSIONS

- COMPLETED THE KINEMATIC AND DYNAMIC MODELING OF THE FACILITY, WITH CONTACT SIMULATION THROUGH THE VIRTUAL FORCE METHOD (IEEE BENEVENTO PAPER, 2014)
- COMPLETED THE MECHANICAL DETAILED DESIGN AND FEM ANALYSIS (STATIC, MODAL AND CONTACT) OF THE MANIPULATOR
- PROCUREMENT COMPLETED AND ASSEMBLY IN FINAL PHASES
- APPLICATION OF CROSS ENTROPY METHOD TO THE PROBLEM OF OSS IN RENDEZVOUS SCENARIOS, TO BE SIMULATED BY THE FACILITY
- DEVELOPED AND MANUFACTURED A MINIATURIZED SUN SENSOR TO BE USED AS A PART OF THE SENSOR SUITE AT THE TIP OF THE END EFFECTOR

Questions?