EXECUTIVE SUMMARY

29TH ANNUAL AHS INTERNATIONAL DESIGN COMPETITION
UNDERGRADUATE CATEGORY

Eliya Wing
Juan Pablo Afman
Michael Avera
Michael Burn
Christopher Cofelice
Peter Johnson

Robert Lee
Ian Moore
Travis Smith
Gökçin Çınar
 Özge Sinem Özçakmak
Yakut Cansev Küçükosman

MIDDLE EAST TECHNICAL UNIVERSITY

Sikorsky
A United Technologies Company

GT BADGER
# CONCEPT DESIGN SUMMARY

## BADGER SPECIFICATIONS

### WEIGHTS

<table>
<thead>
<tr>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empty Weight</td>
<td>lbs</td>
</tr>
<tr>
<td>Max. Gross Weight</td>
<td>lbs</td>
</tr>
<tr>
<td>GTOW</td>
<td>lbs</td>
</tr>
<tr>
<td>Payload</td>
<td>lbs</td>
</tr>
<tr>
<td>Max. Fuel Weight</td>
<td>lbs</td>
</tr>
</tbody>
</table>

### PERFORMANCE @ S.L. 103 F

<table>
<thead>
<tr>
<th>Units</th>
<th>GW 2500 lbs</th>
<th>GW 2800 lbs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Cruise Speed</td>
<td>kts</td>
<td>175.9</td>
</tr>
<tr>
<td>Speed at 90% MCP</td>
<td>kts</td>
<td>165.7</td>
</tr>
<tr>
<td>Best Range Speed</td>
<td>kts</td>
<td>119.8</td>
</tr>
<tr>
<td>Best Endurance Speed</td>
<td>kts</td>
<td>68.6</td>
</tr>
<tr>
<td>Max. Sideward Flight Speed</td>
<td>kts</td>
<td>65.5</td>
</tr>
<tr>
<td>Max Sustained Load Factor</td>
<td>G</td>
<td>3.11</td>
</tr>
<tr>
<td>Course Time</td>
<td>s</td>
<td>247.8</td>
</tr>
</tbody>
</table>

### POWER PLANT

<table>
<thead>
<tr>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Engines</td>
<td>1</td>
</tr>
<tr>
<td>MRP @2 min 103°F S.L</td>
<td>hp</td>
</tr>
<tr>
<td>MCP @ 103°F S.L</td>
<td>hp</td>
</tr>
</tbody>
</table>

### GENERAL DIMENSIONS

<table>
<thead>
<tr>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Blades (per rotor)</td>
<td>2</td>
</tr>
<tr>
<td>Main Rotor Diameter</td>
<td>ft</td>
</tr>
<tr>
<td>Main Rotor Blade Chord</td>
<td>ft</td>
</tr>
<tr>
<td>Main Rotor Disk Loading</td>
<td>lbs/ft²</td>
</tr>
<tr>
<td>Tip Speed</td>
<td>ft/s</td>
</tr>
<tr>
<td>Propeller Diameter</td>
<td>ft</td>
</tr>
<tr>
<td>Flat Plate Area Forward Flight</td>
<td>ft²</td>
</tr>
<tr>
<td>Flat Plate Area Sideward Flight</td>
<td>ft²</td>
</tr>
</tbody>
</table>
A NEW TWIST ON INTERMESHING

- This ain’t your mama’s “air mule”
  Fact: The Badger is no simple “air mule”.
  It has been designed to be a fast and maneuverable pylon racing helicopter

<table>
<thead>
<tr>
<th></th>
<th>Badger</th>
<th>K-Max: the “Air Mule”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max speed @SL STD</td>
<td>170 Knots</td>
<td>100 Knots</td>
</tr>
<tr>
<td>Translational speed</td>
<td>63 Knots</td>
<td>11.9 Knots</td>
</tr>
<tr>
<td>Max TOGW</td>
<td>2500 lbs</td>
<td>12000 lbs</td>
</tr>
<tr>
<td>Power</td>
<td>400 hp</td>
<td>1500 hp</td>
</tr>
<tr>
<td>Disk loading</td>
<td>2.59 lbs/ft²</td>
<td>3.28 lbs/ft²</td>
</tr>
<tr>
<td>Diameter</td>
<td>24.8 ft</td>
<td>48.25 ft</td>
</tr>
<tr>
<td>Overall Length</td>
<td>25 ft</td>
<td>52 ft</td>
</tr>
</tbody>
</table>
| RFP η/Max TOGW (without time) | \[
\frac{.476}{5 \times \frac{128\text{lbs} + 550\text{hp}}{2500\text{lbs}}} = .75 \times \frac{5 \times 1492\text{lbs} + 1500\text{hp}}{12000}
\]

ACKNOWLEDGEMENT OF REQUIREMENTS

- **PERFORMANCE**
  - Max start speed <100 kts
  - Max bank angle of 90°
  - Slung load capabilities
  - HOGE take off @S.L. 103°F, TOGW
  - Cruise at min of 125 kts @90 % MCP
  - 60 kts SW flight @ S.L 103°F, TOGW
  - Time Estimates
  - Fuel burned throughout mission
  - η Function

- **MISSION**
  - One 225 lbs pilot
  - 10 min warm up time
  - 5 min to takeoff
  - 15 min fuel reserve @\(V_{BR}\)
  - 15 ft safety zone
  - Minimum clearance of one rotor radius from moving components
  - MIL STD 850B visibility
  - Floatation/Fire protection for pilot

- **MISCELLANEOUS**
  - Accounted power installation factors
  - Inboard/outboard profiles of helicopter
  - Weight allocations for all components (MIL STD 1374)
  - Pilot feedback
  - Preliminary structural design
  - Avionics suite meeting min FAA req. for NY VFR corridor
DIMENSIONS
Length Overall 25.17 ft
Overall height 12.67 ft
Fuselage width 4.33 ft
Rotor diameter 24.8 ft
Disk loading 2.58 lbs/ft²

ENGINE RATING
(ISA, S.L. 103°)
Number of Engines 1
MCP 424 hp
MRP @ 2 min 550 hp

WEIGHT
Max. TOGW 2800 lbs
Empty 2148 lbs
Max. Fuel 127 lbs
Crew 225 lbs
Slung payload 300 lbs

PERFORMANCE
TOGW@ 2500 lbs (ISA, S.L. 103°)
Best endurance speed 68.4 kts
Best range speed $V_{BR}$ 119.8 kts
Max. speed 175.9 kts
Speed at 90% MCP 165.7 kts
Sideward Flight Speed 65.5 kts
INTERMESHING DECISION

Intermeshing compared to:

Pros

- True lift symmetry in forward flight
- Smaller fuselage length
- Very easy on the pilot
- No tail: more power for main rotors

Cons

- Higher drag
- Higher HP Required
- Not as much control in yaw

Single Main

- True lift symmetry in forward flight
- Smaller fuselage length
- Very easy on the pilot
- No tail: more power for main rotors

- Higher drag
- Higher HP Required
- Not as much control in yaw

Coaxial

- No limitations due to risk of blade tips striking each other
- Significantly simpler transmission
- True lift symmetry in forward flight
- Better sideward flight due to canted rotors
- Very easy on the pilot in terms of controls
- Lower Induced HP Required

- Slightly smaller footprint and width
- Some loss in lift due to canted rotors (%2)

TOPSIS

![Topsis Diagram]

- Single
- Coaxial
- Intermeshing
- Tilt Rotor

![Bar Chart]

- Single Main
- Coaxial
- Intermeshing
- Tilt Rotor
DESIGN SELECTION

- Design Process Flow map

- Georgia Tech’s Integrated Product/Process Development was used during the development of The BADGER
Several trade studies were conducted with respect to material decisions. The primary objective was to effectively choose technologically advanced materials and manufacturing methods that would result in weight reduction while keeping in mind the aircraft’s structural integrity, pilot safety and cost effectiveness.
DRAG BUILDUP

- Empirical drag build-up for forward flight Flat Plate Area (EFPA) of 7.2 ft²

- Computational Fluid Dynamics was used to determine sideward flight Equivalent Flat Plate Area = 41 ft². This allowed The BADGER team to determine and overcome the thrust required to meet RFP requirement of 60kt sideward flight.

<table>
<thead>
<tr>
<th>Component</th>
<th>Parasite Drag (ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuselage</td>
<td>0.822</td>
</tr>
<tr>
<td>Nacelles</td>
<td>0.7263</td>
</tr>
<tr>
<td>Main Rotor Hub</td>
<td>1.9638</td>
</tr>
<tr>
<td>Landing Gear</td>
<td>0.6</td>
</tr>
<tr>
<td>Horizontal Tail</td>
<td>0.101</td>
</tr>
<tr>
<td>Vertical Tail</td>
<td>0.07</td>
</tr>
<tr>
<td>Interference</td>
<td>0.5</td>
</tr>
<tr>
<td>Exhaust</td>
<td>0.5</td>
</tr>
<tr>
<td>Auxiliary Propeller</td>
<td>.912</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>1</td>
</tr>
<tr>
<td>Total Frontal</td>
<td>7.2</td>
</tr>
</tbody>
</table>
PERFORMANCE ANALYSIS

- Successfully outperforms RFP performance requirements with the use of auxiliary propulsion in the form of a pusher propeller for both increased acceleration and deceleration properties.

- Sized to a standard atmospheric temperature of 103 degrees Farenheight, The BADGER’s performance characteristics allow it not only to perform, but outperform the competition even in demanding weather conditions.

<table>
<thead>
<tr>
<th>Parameter (103F)</th>
<th>GW = 2500lbs</th>
<th>GW = 2800lbs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best range speed</td>
<td>119.8312 knots</td>
<td>123.5676 knots</td>
</tr>
<tr>
<td>Best endurance speed</td>
<td>68.5893 knots</td>
<td>73.1264 knots</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>175.8769 knots</td>
<td>174.2756 knots</td>
</tr>
<tr>
<td>Speed at 90% MCP</td>
<td>165.7353 knots</td>
<td>164.134 knots</td>
</tr>
</tbody>
</table>
• Outstanding Lift to Drag Ratios

- The BADGER is able to achieve a 4k ft/min maximum rate of climb

- A plot of minimum turning radius versus velocity was necessary to ensure that our helicopter was capable of performing certain maneuvers expected in the race such as the 300 ft 180 degree turn in the beginning of the track.
CONTROLS AND HANDLING QUALITIES

- Nonlinear synchropter model built in HeliDyn

- Controller Design Includes:
  - SAS
  - Attitude Command Attitude Hold
  - Rate Command Attitude Hold
  - Velocity Hold
  - Altitude hold

- Fly by Light Architecture
  - Replaces mechanical linkages with electronic actuators
  - Reduces weight through use of fiber optic cable
  - Less susceptible to electromagnetic interference than fly by wire systems
  - Electronic actuators allow for easy implementation of a flight control system computer and quick response time which is crucial for a highly maneuverable and agile rotorcraft

- Level 1 Handling Qualities
MAIN ROTOR DESIGN

- Low Disk loading
  - Better maneuverability
  - Limited by RFP size Restrictions

- High Aspect Ratio
  - Decrease in Power Required
  - Structural chord > .05ft

- Highest tip speed possible
  - Increased performance
  - Increased maneuverability
  - Based on VR7b airfoil data

- Blade Element Momentum Theory (BEMT)
  - Used to find optimum airfoil and blade twist

Specifications
- Blades per rotor: 2
- Disk Loading (ft): 2.58
- Radius (ft): 12.4
- Chord: 0.67
- Tip speed (ft/s): 670
- Aspect ratio: 18.6
- Total twist: -10.5°
- Root pitch at operating conditions: 10.62°
- Tip pitch at operating conditions: .125°
- Airfoil: VR7B

Tip Speed vs Average Blade Chord
- N=2
- N=3
- Desired Chord
- Desired Chord
- Boundary Constraints
HUB DESIGN

- Teetering hub with hub spring and feathering bearing. Elastomeric hub spring gives control power at <1 G maneuvers.

- Servo – flap controls collective and cyclic pitch with the advantage of a lower drag hub by removal of pitch links.

- Angle of mast of 13° with 1° precone angle for max flapping angle clearance.

- Ideal mast separation allows Induced Horsepower to be lower than a typical coaxial rotor configuration.
**AUXILIARY PROPULSION**

- Used to reduce the effective flat plate drag during accelerations
- Removes tendency of rotor to pitch rearward in forward flight

- Sized to produce enough thrust to counteract 80% of drag at 140 kts forward speed
- Badger incorporates a one sided rotatable horizontal stabilizer to cancel torque produced by aux prop

**Dimensions**

- Diameter: 6 ft
- Mean Chord: .425 ft
- B at .75c: 28.1°
- Number of Blades: 6
- Solidity: .271
  - MH 126
  - MH 112
  - MH 116
- Airfoils: MH 126, MH 112, MH 116

**Performance**

- V/nD: 1.026
- Thrust: 511 lbs
- Power Required (at 170 knots): 146.4 hp
- Efficiency: 79%
- RPM: 2300
TRAJECTORY OPTIMIZATION

- Optimal control theory combined with human-pilot based constraints
  - GPOPS (General Pseudospectral OPtimal control Software)

Best time of 4 minutes and 8 seconds

TRANSMISSION DESIGN

- Adequate transmission sizing was performed
ENGINE SIZING

RFP Requirements
- 125 knots at 90% MCP
- Ability to pull a 3g turn (limiting factor)
- Ability to fly 60 knots sideways
- Must minimize the scoring function by finding the minimum MRP required and minimum fuel consumption
- Scaled engine using equations given in RFP

Appropriate calibrations were performed on The BADGER’s engine to comply with RFP regulations and requirements

<table>
<thead>
<tr>
<th>SL/ISA</th>
<th>SL/103°F</th>
<th>6K/95°F</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HP</td>
<td>SFC (lb/hp*hr)</td>
</tr>
<tr>
<td>OEI</td>
<td>703.6</td>
<td>0.378</td>
</tr>
<tr>
<td>MRP</td>
<td>672.1</td>
<td>0.379</td>
</tr>
<tr>
<td>IRP</td>
<td>626.5</td>
<td>0.384</td>
</tr>
<tr>
<td>MCP</td>
<td>512.4</td>
<td>0.398</td>
</tr>
<tr>
<td>Part Power</td>
<td>336.0</td>
<td>0.448</td>
</tr>
<tr>
<td>Idle</td>
<td>134.1</td>
<td>0.706</td>
</tr>
</tbody>
</table>

\[
\text{Diameter} = 2.117 \cdot \left(\frac{\text{MRP}_{\text{uninstalled SL/ISA}}}{110.0}\right)^{0.3704}
\]
\[
\text{Length} = 2.622 \cdot \left(\frac{\text{MRP}_{\text{uninstalled SL/ISA}}}{110.0}\right)^{0.4148}
\]
STRUCTURAL AND INTERNAL LAYOUT

- Lightweight aluminum airframe composed of I beams, box beams, and solid beams
- Two primary bulkheads to carry crash loads and main aerodynamic loads
- Nose plate used to connect bottom I beam two side box beam longerons
- Advantageously placed internal systems to maintain a center of gravity along the auxiliary propulsion thrust vector
- Internal systems attached to upper I beam and longerons as well as front bulkhead to optimize load paths
- Load hook mounted on the bottom I beam to support 300 lb slung load
- Aluminum hollow tube crashworthy landing gear
- FEA landing gear and airframe test conducted using ANSYS static structural toolbox
- Crash loads approximated with a 2g load factor on landing gear supports and 4g on airframe
SAFETY CAPABILITIES

- 5 Point harness BAE S7000 crashworthy seat that meets MIL – 58095A and MIL – STD -810 safety requirements

- Phantom 5 minute emergency oxygen tank allowing pilot to survive underwater while emergency personnel perform rescue mission

- Portable and compact fire extinguisher that allows The BADGER to comply with the requirements given by the 2012 RFP regarding fire protection

- Small and light weight military designed inflatable raft which allows The BADGER to comply with the requirements given by the 2012 RFP regarding flotation for the pilot

- Autorotative index of 22.5 for the unfortunate case of an engine failure during the race
Cockpit Design

- High-visibility cockpit design based on Marenco Swisshelicopter concept. Planes of vision meet MILSTD-850B requirements.

- Heads-Up Display (HUD) projecting optimized trajectory course onto windshield for pilot aid during race.

- Dynon Skyview 7” Electronic Flight Instrumentation System (EFIS).
  - Contains Primary Function Display (PFD), Moving Map, and Engine Monitoring.
  - Installed with “soft stop” alerting system (EICAS) to alert pilot in event of critical engine levels or approaching any helicopter limits.

- Quick release switch for cargo hook in case of an unexpected emergency landing is required.
TOP TEN TRADE STUDIES

1. Intermeshing vs. Other Configurations
2. Auxiliary Yaw control
3. Auxiliary Forward propulsion
4. Hub Configuration
5. Main Rotor and Airfoil selection
6. Mast Separation
7. Transmission Selection
8. Electric Propulsion
9. Material Selection
10. Cockpit Technologies

- Based off of the trade study results, all technologies used are currently on the market
- The Badger is a TRL of 7.5, this places it in “The System Development phase”
- Five Year Expected Production

COST ANALYSIS

Average production cost per helicopter: $1,689,926
GT – BADGER: WE’LL SEE YOU AT THE RACE LINE

- The BADGER’s official $\eta = 1380.6$
- All RFP requirements are 100% satisfied
- The BADGER is a highly maneuverable unconventional agile rotorcraft
- Its unique intermeshing rotor configuration separates it from conventional designs
- The auxiliary propulsion system allows for incredible acceleration and deceleration during the race