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Photo by Ignus Dreyer

Industry Day
Closing the Gap: Autonomous Control for Satellite Rendezvous and Docking

Stellenbosch University
2026

Stellenbosch Space Heritage

From Africa's first satellite to international nanosatellite missions

1992–99

SUNSAT

Africa's 1st microsatellite

Built by SU postgrads. Launched on Delta II, Feb 1999 — 64 kg, proving African-built satellites could reach orbit.

2000

SunSpace

Industry spin-out

SUNSAT team commercialised — founding SunSpace in 2000, seeding Stellenbosch's now-thriving global space industry cluster.

2009

SumbandilaSat

South Africa's 2nd satellite

81 kg — contracted by SA Dept of Science & Technology to SU. ESL & SunSpace co-delivered. Launched Soyuz, Sept 2009.

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Commercialization and further development of of attitude determination and control systems (ADCS) for small satellites.

2014–17

QB50 & DeOrbitSail

EU FP7 debris programmes

SU contributed two CubeSats to QB50's 50-satellite thermosphere network. DeOrbitSail drag-sail technology partner (FP7).

2018

RemoveDebris

Active Debris Removal mission

SU ESL avionics flew on DebrisSat-2. Partners: Surrey, Airbus, ArianeGroup — in-orbit active debris removal demo.

2018-Present

Space Robotics

Development of future space

Development of miniaturize autonomous satellite systems which can execute rendezvous and docking mission

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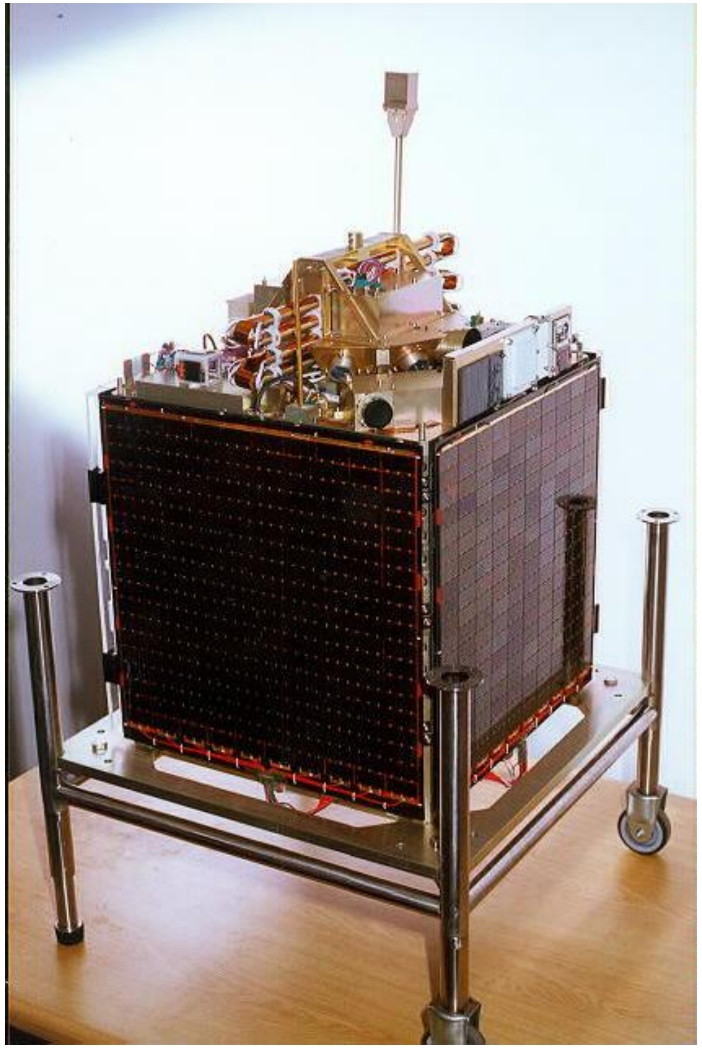
SUNSAT Project

- Africa’s first indigenous (locally built) orbiting satellite
- Satellite was designed and developed without any technology transfer help
- Developed by graduate students and staff in period 1992-1998
- **Produce more than 100 Masters and PhD degrees**
- First microsatellite (64kg) with SPOT-5 type 3-band multispectral resolution camera
- 3456 pixel push-broom sensor giving a 52 km swath and 15 m GSD from 800 km



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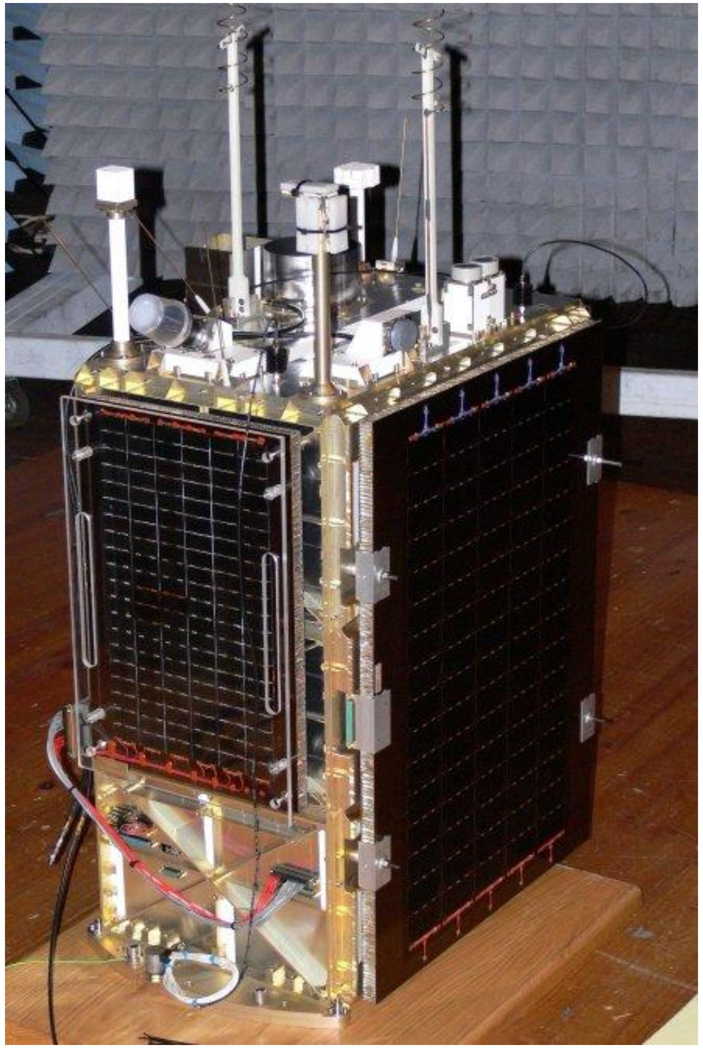
Sumbandila Project

- 83 kg Microsatellite (DST sponsored)
  - 505 km 9 am/pm sun-synchronous orbit
  - 6.25 m GSD Imaging in 6 spectral bands
  - Viewfinder for real time image steering
  - 24 Gbyte onboard image storage
  - 3-Axis Reaction wheel stabilized
  - Email Communication system
  - Propulsion system for drag compensation
  - Expected orbital life 3-5 years
- Satellite build by SunSpace in 15 months
- Stellenbosch University did the project management and ADCS development
- **Large training and capacity development program**
- Launch 17 Sept 2009 @ 17h55:07 GMT from Baikonur Kazakstan on a Soyuz-2 rocket



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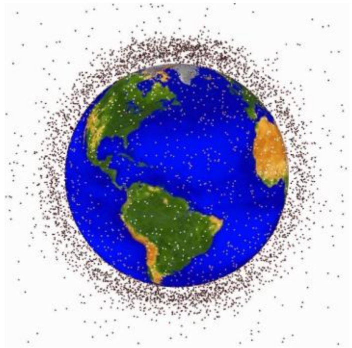
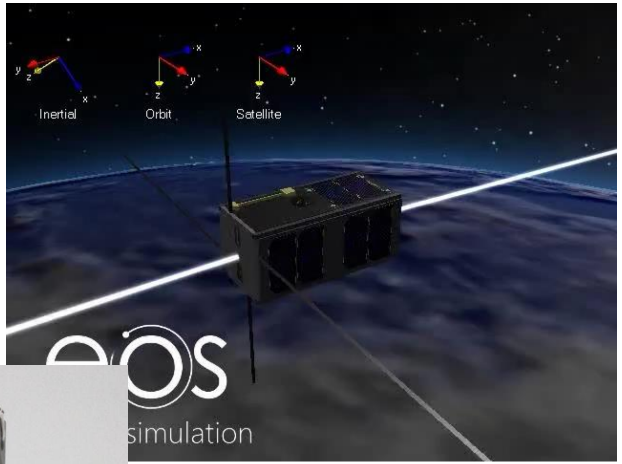
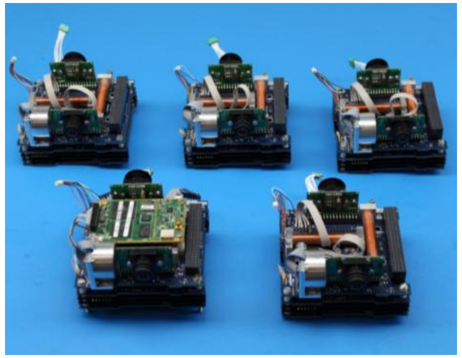
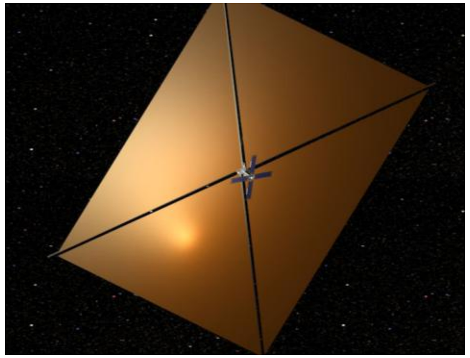
QB50 & DeOrbitSail

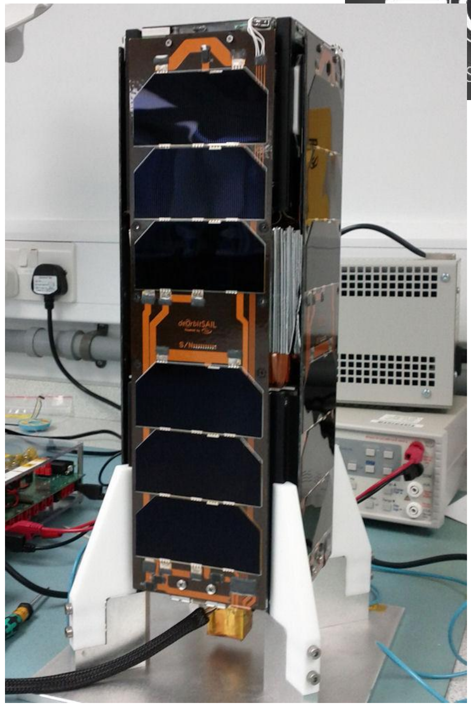
- Developed and built 18 ADCS units along with Surrey Space Centre for participants
- South Africa’s QB50 Satellites
  - ZA-AeroSat 2U CubeSat from Stellenbosch University (ESL & CubeSpace)
  - nSight-1 2U CubeSat from Space Commercial Services (SCS)
- Developed custom control avionics for passive deorbit device

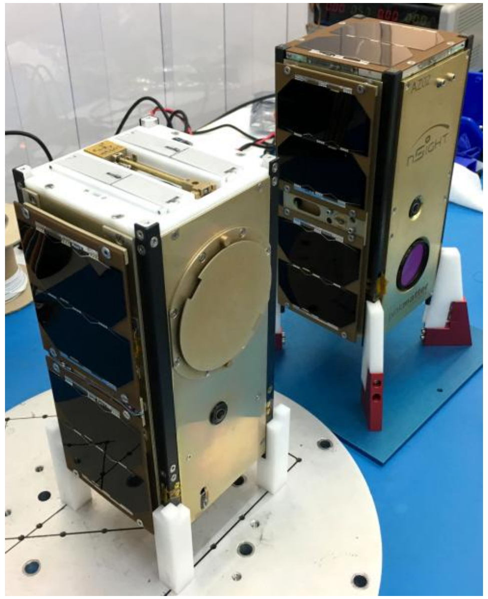












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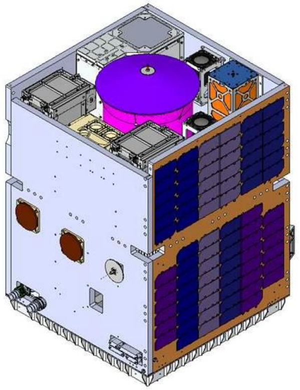
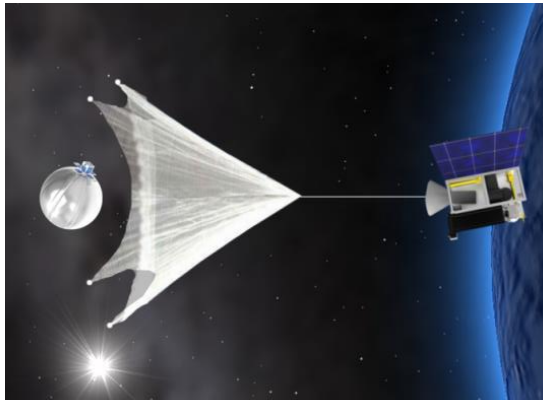
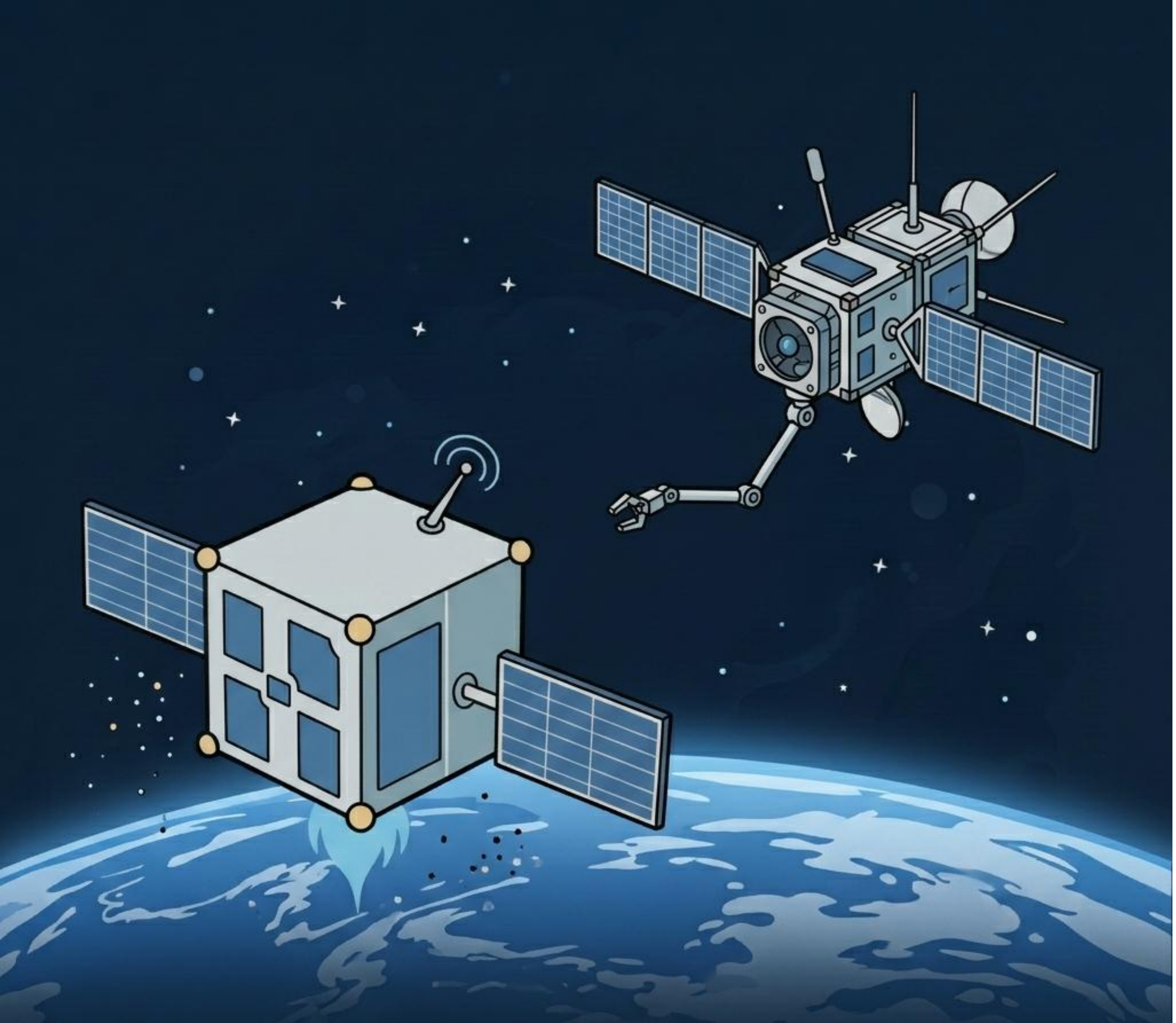
RemoveDebris

- RemoveDebris Project Aims:
  - Chaser microsatellite release 2 Debris CubeSats
  - Demonstrate automatic removal using a net and a harpoon to capture "debris"
  - De-orbit "debris" using inflatable balloon, tether







The Problem

Orbital servicing, debris removal, and constellation logistics all hinge on one unsolved challenge – controlling the gap between satellites

Why This Matters Now

The market, the problem, and the strategic moment

$~5B

In-orbit servicing market

by 2030 — growing at ~12% CAGR

130M+

Debris objects in orbit

Only ~54,000 are trackable (>10 cm)

40%+

Cost savings: service vs. replace

NASA analysis — hardware outlives fuel

Constellation Boom Drives Servicing Demand

Thousands of LEO satellites (Starlink, OneWeb, etc.) have created urgent demand for life-extension, inspection, and orbit adjustment — all requiring autonomous rendezvous & docking.

Regulatory Pressure is Intensifying

ESA's 2025 Environment Report confirms debris grows even with no new launches. Governments and regulators are moving toward mandatory ADR compliance — creating near-term procurement demand.

Replace = Unaffordable & Unsustainable

Satellites typically run out of fuel before hardware fails. Servicing at a fraction of replacement cost is now commercially viable — but only with autonomous proximity operations.

Sources: MarketsandMarkets / ESA Space Environment Report 2025 / NASA NTRS / Aerospace Corp. CSPS / SANSA Strategic Plan 2025-30

What Makes R&D Hard

Six interlocking technical challenges

⚖️ 6-DOF Relative Motion

Chaser and target move in 6 degrees of freedom simultaneously. Small thruster errors compound rapidly at close range.

📡 Comms Latency & Loss

Ground control loops are too slow. Fully autonomous GNC is mandatory — decisions must be made on-board in real time.

🎯 Sensor Noise & Uncertainty

LiDAR, cameras, and IMUs all carry noise. State estimation must fuse multiple sensors under tight power and mass budgets.

🌀 Non-Cooperative Targets

Dead satellites tumble unpredictably. No docking port, no reflectors, no cooperation — the chaser must adapt on the fly.

🌍 Orbital Mechanics

Clohessy-Wiltshire dynamics mean intuitive manoeuvres fail. Fuel-optimal trajectories require constrained optimisation in real time.

🔁 Sim-to-Real Transfer

Ground-based simulation can't perfectly replicate microgravity + vacuum + real sensor noise. Models must be robust to the gap.

These challenges do not occur in isolation. Solving them together, autonomously, in real time, is the research problem.

The Autonomy Stack

How the system works end-to-end — from raw sensor data to thruster command

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01

Perception

Sense the target's position, shape and motion relative to the chaser spacecraft.

INPUTS

LiDAR · Stereo Camera
IMU · Star Tracker

OUTPUTS

Raw point clouds
Image frames

02

State Estimation

Fuse noisy sensor streams into a clean, real-time estimate of relative state.

INPUTS

Sensor fusion (EKF/UKF)
Pose estimation (6-DOF)

OUTPUTS

Relative pos, vel
Attitude estimate

03

Guidance

Plan a fuel-optimal, collision-free approach path using CW dynamics + MPC.

INPUTS

Relative state
Mission constraints

OUTPUTS

Reference trajectory
Waypoints

04

Control

MPC + RL hybrid closes the loop — safe by design, adaptive by learning.

INPUTS

Reference trajectory
Current state error

OUTPUTS

ΔV commands
Attitude setpoints

05

Actuation

Execute commands on cold-gas thrusters and reaction wheels — verified on HIL testbed.

INPUTS

ΔV / torque commands
Flight computer

OUTPUTS

Thruster firings
Reaction wheel cmds

◄ *closed-loop feedback (state estimate updates guidance & control continuously)*

Every layer runs on-board — no ground-in-the-loop. The system operates fully autonomously from first detection through to docking contact.

DockSat

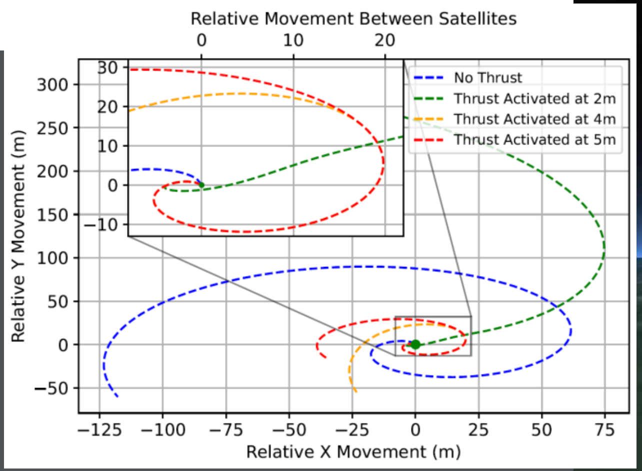
Conceptual mission demonstrating the in-orbit docking of nanosatellite.

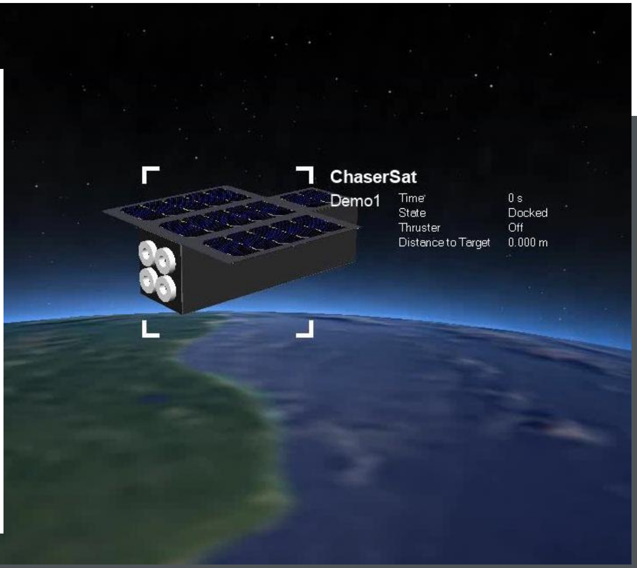
Require propulsion, accurate attitude control, pose estimation and custom docking mechanism.

Orchestrating 6-DOF Motion

Autonomy Stack

- Perception
- State Estimation
- **Guidance**
- **Control**
- Actuation





ChaserSat

Demo1

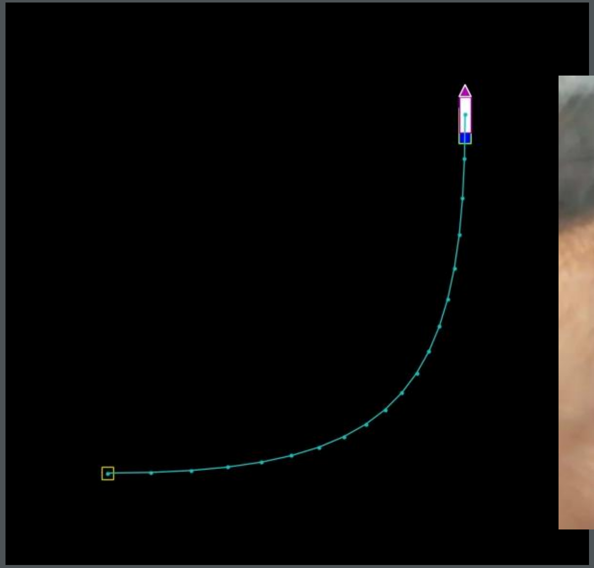
Time: 0 s

State: Docked

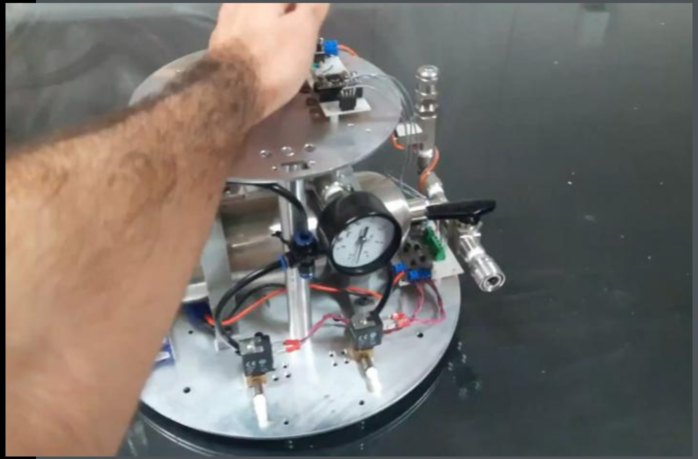
Thruster: Off

Distance to Target: 0.000 m

Simple docking planning



Guidance controller docking with static target



Planar Air-bearing for Practical Tests

Low-Thrust Optimization Orbital Planning

The implemented planners optimize trajectories to minimize fuel consumption while ensuring the chaser satellite reaches the target at the precise approach velocity required for docking.

Formation Control

Model predictive control algorithms are developed which can ensure accurate relative positioning of satellites.

Planning for Movement

Developing algorithms which predicts the future movement and pose of dynamic target and plan a trajectory to successfully dock.

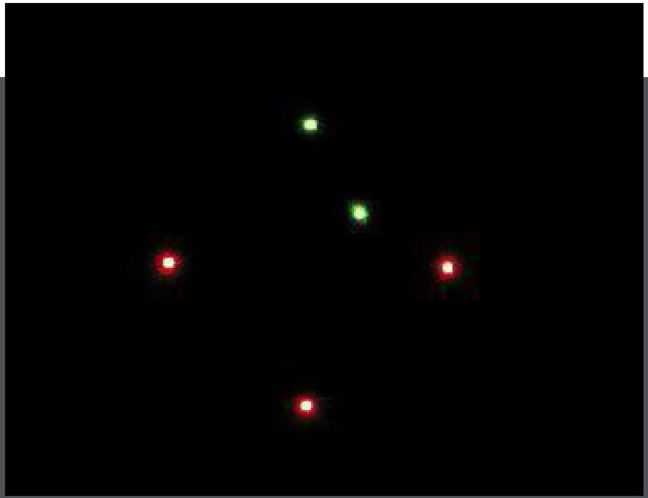
Practical Verification with Air Bearing

Making use of Dark Room with Planar air bearing to facilitate the verification of guidance algorithms.

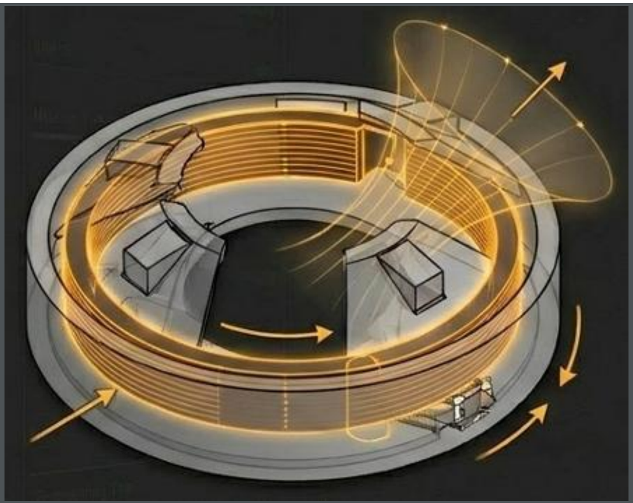
The Mechanics of Connection

Autonomy Stack

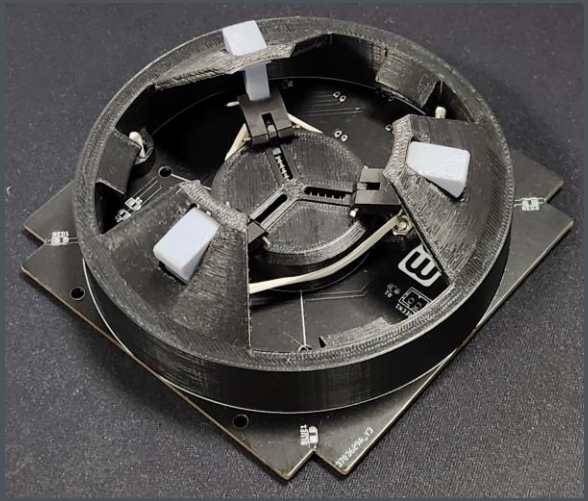
- Perception
- State Estimation
- Guidance
- Control
- Actuation



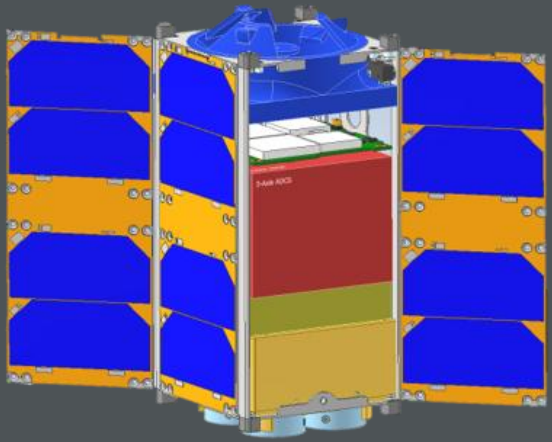
Practical Identification of Fiducial Markers



Magnetic force provide precise pull



Docking Mechanism Prototype



DockSat with Docking Mechanism

Tuna-Can Volume

The mechanical challenge of miniaturizing international Docking System Standard (IDDS) principles into CubeSat footprint.

Androgynous & Lockable

Employs an androgynous petal design with low-friction shifters and a secure locking spindle to ensure hard capture alignment.

Integrated Electromagnetics

The PCB back-plane co-houses the pose estimation LEDs alongside custom-wound electromagnetic coils, enabling dipole-to-dipole magnetic force control in the final docking phase.

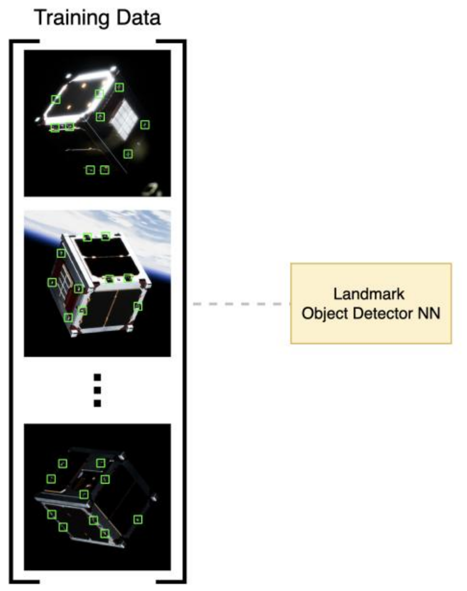
Geometric Optical Fiducials

The docking adaptor houses a modified 5-LED pattern (4 in-plane and 1 out-plane marker) allows the Chaser to have rapid, low-compute analytical pose estimation during close-proximity.

Deep Learning via Synthetic Data

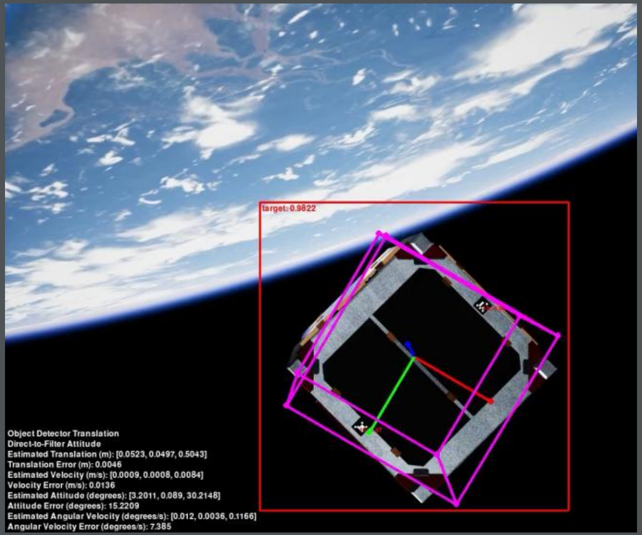
Autonomy Stack

- Perception
- State Estimation
- Guidance
- Control
- Actuation



Training an object detector to localize landmarks on target.

Photorealistic Virtual Space Environment



```
Object Detector Translation
Direct-to-Filter Attitude
Estimated Translation (m): [0.0523, 0.0497, 0.5043]
Translation Error (m): 0.0046
Estimated Velocity (m/s): [0.0009, 0.0008, 0.0084]
Velocity Error (m/s): 0.0136
Estimated Attitude (degrees): [3.2011, 0.089, 30.2148]
Attitude Error (degrees): 15.2209
Estimated Angular Velocity (degrees/s): [0.012, 0.0036, 0.1166]
Angular Velocity Error (degrees/s): 7.385
```

Direct-to-Filter attitude estimation on rendezvous scenario.

Overcoming the Sim-to-real Gap

Real-life orbital rendezvous datasets are virtually non-existent. We utilize Unreal Engine to generate photorealistic synthetic training data.

Hybrid Pose Estimation Pipeline

- **AIBB Extraction:** An object detector neural network predicts bounding boxes modified to retain valuable depth relationships regardless of attitude.
- **2D-3D Correspondence:** The network isolates specific landmarks, mapping 2D image coordinates to 3D model geometries to output a robust translation prediction before passing data to filter

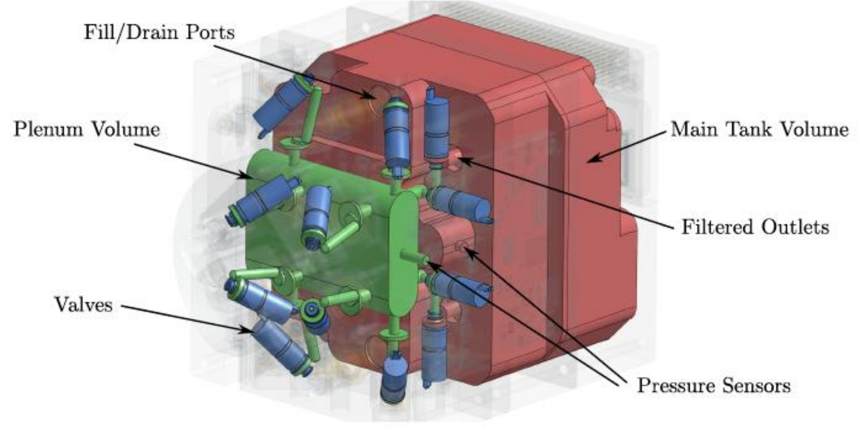
Direct-to-Filter Architecture

The method routes 2D-3D landmark correspondences straight into estimation filter. This approach maintains stable state tracking through extreme, sequential illumination variations inherent to Earth orbit

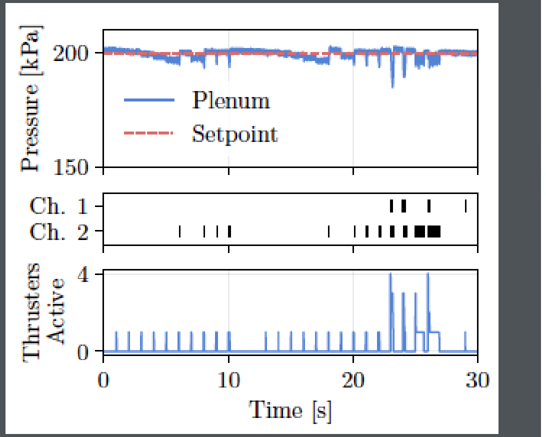
Reaction Control Systems: The Muscles

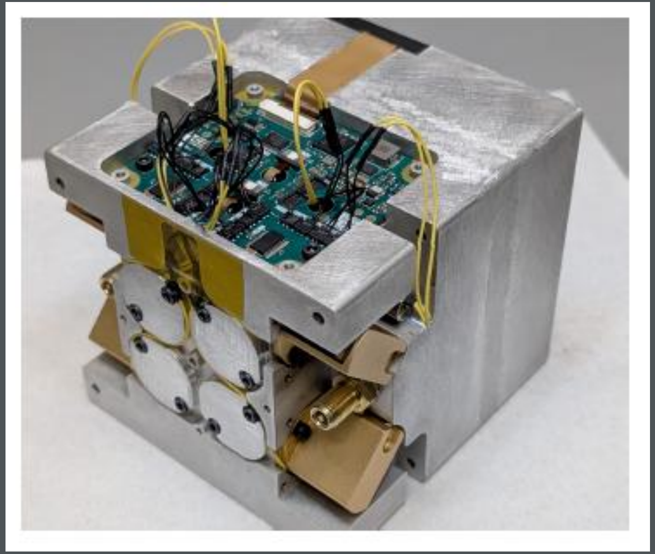
Autonomy Stack

- Perception
- State Estimation
- Guidance
- Control
- Actuation



Thruster module showing eight ports and plenum volume





Prototype with embedded control electronics

Cold-Gas Thruster Iteration

Precision control algorithms algorithms require highly responsive hardware. We developed modular thruster modules designed specifically for edge-case orbital maneuvers.

Two-Phase Control

The constructed module can handle high-pressure two-phase cold-gas propellants (such as Butane/R-245fa), ensuring exactly metered ΔV execution.

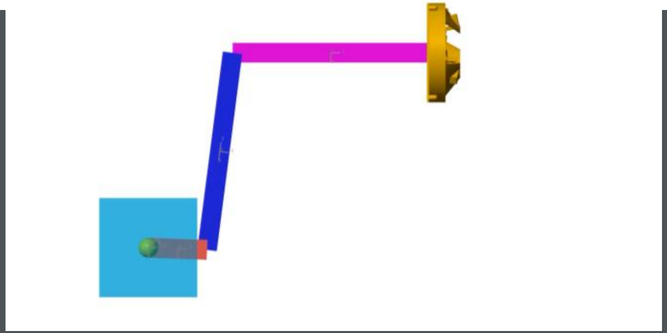
Integrated Environmental Regulation

The module features onboard resistive heaters and a redundant four-valve plenum system (two-parallel, two-series) to autonomously maintain precise propellant pressure and temperature.

Robotic Capture Arm: Extending Reach

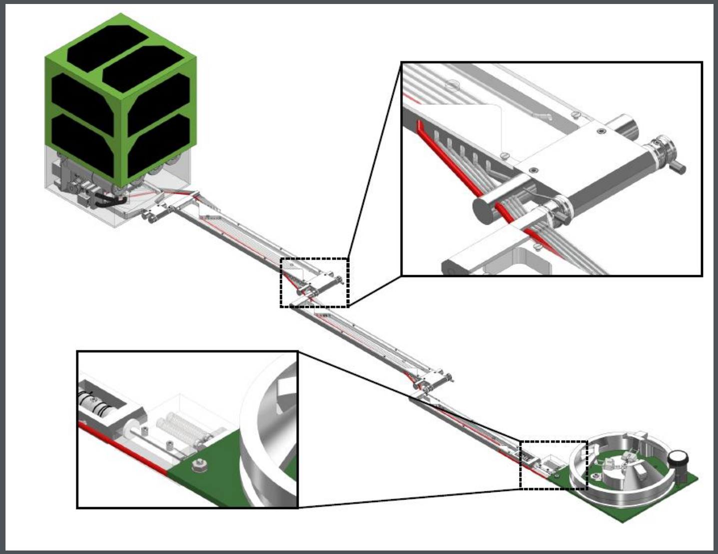
Autonomy Stack

- Perception
- State Estimation
- Guidance
- Control
- Actuation



Floating base Manipulator

Two-link Cable Driven Robot Arm



Full Cable-Driven Arm Design

Kinematic Capture Arm

Optimal kinematic design of a robotic manipulator to drastically increase the probability of successful mechanical capture under low close-proximity control.

Slender Cable-Driven Architecture

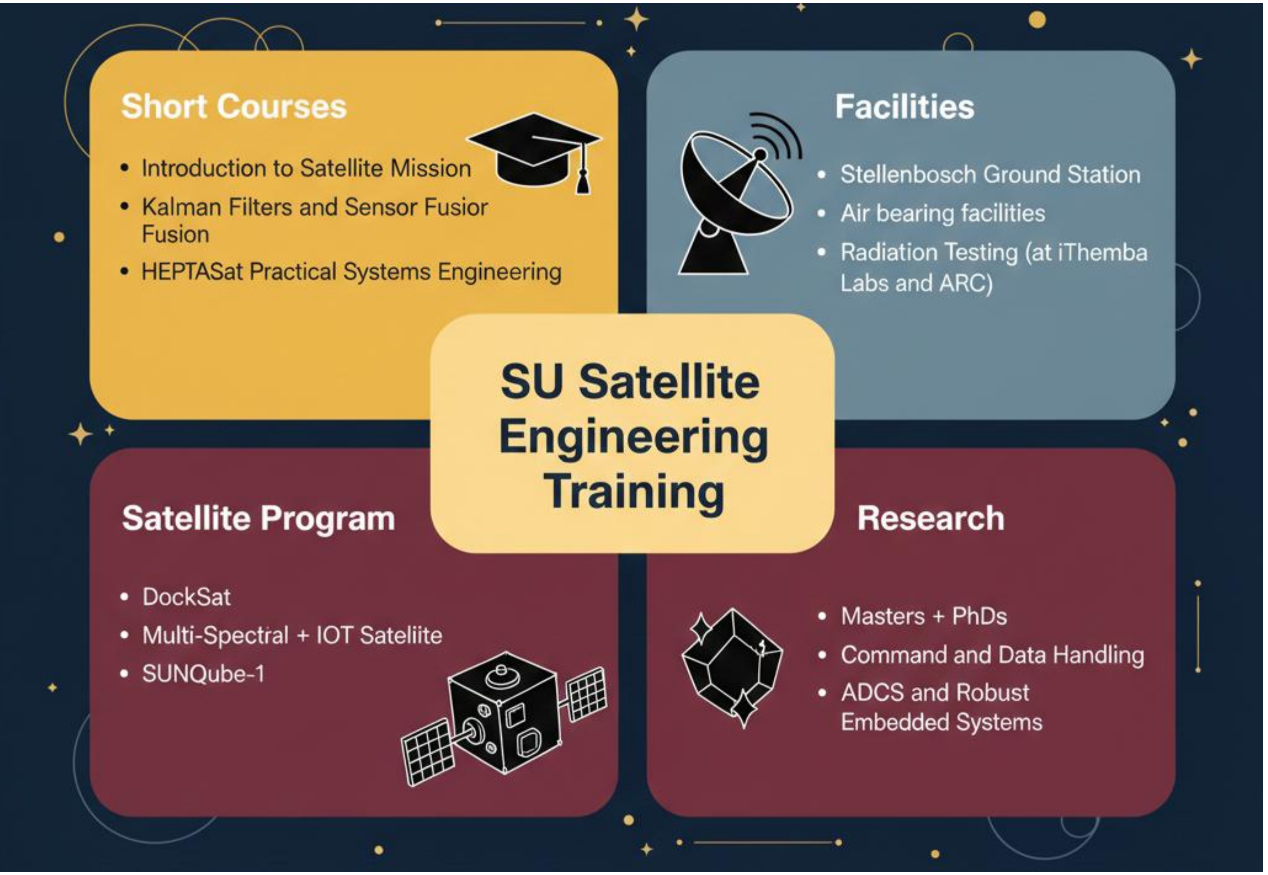
To meet strict CubeSat volume constraints, the arm features an extremely slender profile powered by a remote cable-sheath transmission system.

Reaction-Aware Motion Planning

The capture arm utilizes a specialized motion planning system designed to minimize base reaction torques and velocities on the chaser nanosatellite. This ensures that the spacecraft's attitude remains stable during deployment and capture, preventing the arm's movement from overwhelming the satellite's low-authority reaction control system.

Satellite Engineering Ecosystem

Developing the critical-mass of of space professionals with specialized skills



SU Satellite Engineering Training

Short Courses

- Introduction to Satellite Mission
- Kalman Filters and Sensor Fusior Fusion
- HEPTASat Practical Systems Engineering

Facilities

- Stellenbosch Ground Station
- Air bearing facilities
- Radiation Testing (at iThemba Labs and ARC)

Satellite Program

- DockSat
- Multi-Spectral + IOT Sateliite
- SUNQube-1

Research

- Masters + PhDs
- Command and Data Handling
- ADCS and Robust Embedded Systems

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Thank you
Enkosi
Dankie

Photo by Stefan Els