Artificial Intelligence at the Jet Propulsion Laboratory

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Talk outline

- Included:
  - Overview of JPL
  - Current planning systems
    - ASPEN (batch)
    - CASPER (continuous)
  - Currently complex autonomy systems
    - ASE (Earth)
    - OASIS (+ AEGIS) (Mars)
    - MISUS (Multi-agent Mars)

- Not included
  - In-depth planning and scheduling (see NAIL071)
  - MSL (Curiosity)
  - mathematical formulae

A brief overview of JPL

- formally established 1943 as a US Army facility
- together with W. von Braun launched US' first satellite in '58
- December '58 transferred under NASA
- notable missions
  - practically all successful missions to Mars
  - first mission to Venus
  - Near-Earth object program

- ca. 0.75 km^2
- ca. 5000 Caltech employees, 1000s of other contractors

ASPEN

- Automated Planning/Scheduling Environment
- Architecture:
  - Activity database
    - activities have durations, use resources, require particular states
    - activities may be organized into a hierarchy
    - the DB also manages global constraints
  - Temporal constraint network
    - temporal constraints between activities – e. g. A must be after B
  - Resource timelines
    - resources may be depletable (fuel) or non-depletable (power)
    - all resources are discretized
  - State timelines

CASPER

- continuous planner
- based on ASPEN
- iterative repair
- basic workflow:
  - A plan exists
  - When a status update arrives, search plan for conflicts
  - resolve one by one until no conflicts remain
  - resolution
    - moving, adding, detailing/abstracting activities, modifying temporal constraints,…

ASE

- Autnomous Scienceecraft Experiment
- onboard Earth Observing 1 (EO-1)
- used for:
  - live replanning
  - selection of data for downlink
    - „interesting“:
      - event detection
      - feature detection
      - change detection
      - unusualness detection

EO-1

- Earth Observer 1
- circular 705 km sun-synchronous orbit
- Launched November 21, 2000
- orbit takes approx. 100 minutes
- ~49000 images taken so far
- processors
  - 2x 12MHz, 256MB RAM

EO-1 Onboard instruments

- Hyperion spectral instrument
  - 30m spatial resolution
  - 7.7 x 42 km on all channels (220 – 12 in use at once, 6 const (cloud cover), 6 varied)
- Advanced land imager
  - sophisticated linear camera
- Atmospheric corrector
  - takes measurements of atmospheric effects
  - thus improves quality of images

ASE: Layered architecture

- CASPER
  - top level – continuous planner
  - timescale: tens of minutes (several orbits)
  - responds to observations, science goals,…
  - "lite STL"

ASE: Layers cont.

- SCL
  - middle layer
  - timescale: several seconds
  - expansions of CASPER activities
  - considers spacecraft constraints, flight rules
  - runs scripts of low-level commands
  - monitors spacecraft state and resources, passes back to CASPER
- FSS
  - runs low level commands
  - full fault protection (such as „do not point camera at sun“)

ASE: Onboard science

- Examples
  - volcanoes
    - infrared
    - amount of thermally active pix
  - ice caps
    - change over time
  - clouds
    - 6 bands
    - results used to discard images with high cloud cover, perhaps reimage the area
  - floods
    - different spectral bands to differentiate water from land
    - change over time

ASE in Sensorwebs

- Sensorweb:
  - "system of systems"
  - a network of satellites and ground sensors
- Components:
  - ground sensors, satellites
  - science agents:
    - convert sensor output to "science events"
    - output readable XML
  - science event manager:
    - converts "science events" to observation requests (for EO-1)
    - uses expert input

ASE: some active Sensorwebs

- Widlfires
  - data from other satellites to detect active fires
  - EO-1 acquires more data (higher resolution)
- Floods
  - again, different satellites provide alerts
  - EO-1 acquires more data
- Volcanoes
  - Ground sensors and satellites detect volcanic activity
  - EO-1 acquires more data (a lot of infrared)
- Cryosphere
  - snow melts and triggers….
  - more data from EO-1

ASE: operations flow comparison

- Past
  - weekly
    - manually select 1-2 targets per orbit
    - manually schedule downlinks
  - daily
    - assemble maneuvers for imaging
    - further conflict resolution
    - command seq. uplink
    - reaction to fleeting event in days (or next weekly meeting)
- Present
  - weekly
    - only prioritization of targets is required
    - downlinks scheduled automatically
  - daily
    - only high level goals uplinked
    - reaction to fleeting event as fast as a single orbit

ASE: Challenges

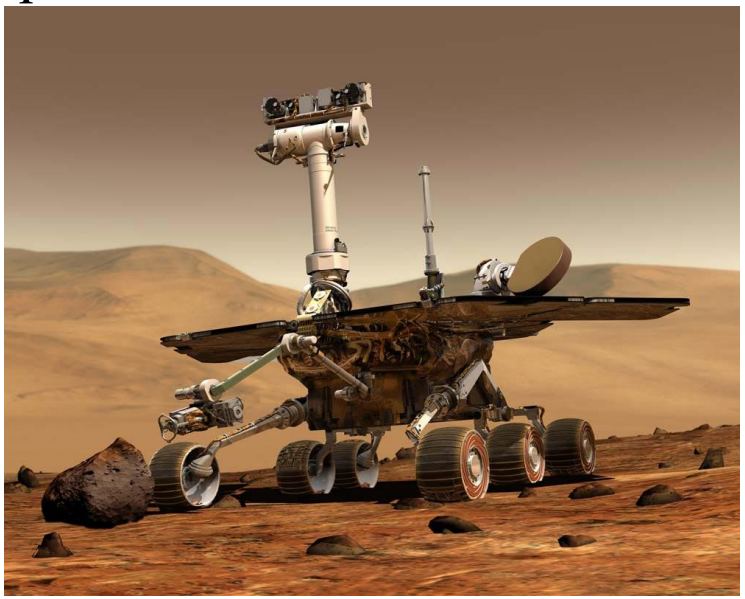
- Challenges
  - operation without communication
    - 8 ground contacts / day, 10-15 mins each, 2Mbit/s DL, 2Kbit/s upload
  - unique equipment
  - limited telemetry
  - limited computing power
  - $$$ (but overall, ASE saves about 1M$ annually)

OASIS

- Onboard Autonomous Science Investigation System
- currently on MERs – Spirit and Opportunity
- Basic structure
  - Feature detection
  - Data analysis and prioritization
  - Planning and scheduling

MER: instrumentation

- Imaging
  - Hazcams (l20° FOV)
  - Navcams (45° FOV)
  - Pancam (l6° FOV)
  - Microscopic imager (tiny FOV)
- Spectrometers (all for rock compositions)
  - Thermal emissions (Mini-TES)
  - Mössbauer (gama rays)
  - Alpha particle X-ray
- Rock abrasion tool
- Magnet array



OASIS: feature detection

- Segmentation
  - rock detection
    - preprocessing
    - edge detection
    - contours
  - sky detection
    - find seeds (is sky present?) – low variance areas
    - identify low variance edge
    - grow seeds
    - determine skyline, horizon

OASIS: feature detection

- Feature extraction
  - Cloud detection
    - locate sky
    - search for high variance regions in the sky
  - Dust devil detection
    - noise reduction
    - compare test image vs. average -> dust devils
  - Rock properties
    - albedo, texture, shape, size
  - Boundary detection
    - geomorphological units

OASIS: Data analysis

- Four approaches:
  - Event detection
    - for cloud and dust devil detection
    - images where nothing is detected need not be downlinked
  - Key target signature
    - for rock detection
    - scientists specify desired properties of high-interest rocks
    - each detected rock is evaluated according to desired properties

OASIS: Data analysis cont'd

- Novelty detection
  - difference from the norm for the region
    - distance-based (distance to nearest rock feature vector cluster)
    - probability based (probability of rock being generated by distr. of other rocks)
    - discriminative (all other rocks form a point cloud in the feature space, its boundary is calculated, new sample in/out)
- Representative sampling
  - (almost) opposite of Novelty detection
  - choose rocks representative of region
  - cluster rocks, choose rock closest to mean

OASIS: planning and execution

- Detected targets of interest are transformed into goals
- goals are passed on to planning software
- plan is updated
- challenges:
  - prediction of power consumption & task duration
    - downlinks
    - movements (unknown terrain)
  - position estimation

OASIS: Planning and execution

- CASPER & TDL
- TDL performs similar functions as SCL

- Planning is capable of handling "science alerts"
  - stop
  - drive somewhere else
  - aim instruments at something
  - acquire more data
  - repeat?
  - talk to Earth?

OASIS: onboard science capabilities

- opportunities during traverse
  - considerable speed-up
- science campaigns
  - such as dust devils, clouds,…
- automated target selection
  - idle instruments ate end-of-day automatically assigned targets
- prioritization when idle (before downlink)

Comparisons

- ASE
  - plans continuously
  - analyzes acquired data
  - decisions:
    - take picture again?
    - downlink?
  - priorities set from ground
- OASIS
  - plans continuously
  - analyzes acquired data
  - decisions
    - take more pictures? which instruments?
    - drive somewhere else?
    - downlink?
  - priorities determined onboard as well as on ground

AEGIS

- onboard system for increased autonomy
- carries out a subset of OASIS tasks
- planned as an independent unit

AEGIS: workflow

- Capture large FOV image with Navcam
- detect areas of interest
  - rocks – found using edges, contours
- extract relevant features
  - size, shape, reflectance
- prioritize targets
  - according to previously set goals
- point other instruments
- acquire new data
  - using Pancam/MI

MISUS

- Multi-rover Integrated Science Understanding System
- Autonomous multi-agent system (proposed & tested)
- Similar to ASE and OASIS, except for the multi-agent part:
  - Data analysis & prioritization
  - (Re)planning according to data
- Main goal
  - find relationships between geological data over large areas
  - => unsupervised learning, clustering

MISUS: distributed planning

- Based on CASPER
- Centralized part
  - limited knowledge of rover resources
  - limited communication (obstructions, distance)
  - global objective: minimize traverse distance
- Distributed part
  - as described before – continuous, iterative repair
  - communication with central planner:
    - receive goals
    - update as goals executed

MISUS: interdependent goals

- modified objective function:
  - each goal has an assigned reward
  - each combination of goals may have an assigned reward
  - plan quality is evaluated as a sum of
    - rewards for completed goals
    - rewards for completed combinations of goals

Summary

- Two essential onboard capabilities:
  - Data analysis (mostly image processing)
  - Replanning
- At JPL:
  - various image processing techniques for analysis
  - CASPER engine for planning
  - Live systems:
    - ASE for EO-1 over Earth
    - OASIS + AEGIS for Mars Exploration Rovers
  - Testing
    - MISUS for more than 1 rover

That's all, folks!

Q&A