D4D - Space Operations

Software Development Plan

Introduction

This is document describes the goals, requirements, development and test plan for software used in the CU Boulder Design for Defense (D4D) course in Spring 2020 that examines the operational requirements for managing space operations. This work focuses on how machine learning and artificial intelligence (ML/AI) can be used to improve operator effectiveness.

Architecture

The software architecture consists of

- Scenario Generation
- Recommendation Engine
- Operator Interface

The recommended initial plan is to generate scenario data (truth and observations) using Python[1], manage the data archival and workflow using the Pachyderm hub[2], model the Recommendation Engine in Python and create a web-based Operator Interface

Scenarios

Current - January 2020

Based on the current USAF catalog of objects in space[3] and a set of simulated sensors generate synthetic data for a variety of scenarios. The approach is to have a set of truth data that represents objects in space and sensors that generate observations of these objects.

The truth data consists of the USAF catalog plus additional objects that produce specific use cases.

For the most part we can view all use cases as variations on three themes

1. Object was detected and correlates with a known object
2. Known object was not detected when expected
3. Unknown object was detected

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[1] Primarily Python libraries Skyfield and Poliastro

[2] pachyderm.com

[3] See space-track.org for a copy of the current catalog

The current day use cases include

- Missed observation - sensor did not detect
- Missed observation w/unknown object detected - possible object maneuver
- Missed observation w/multiple unknown objects detected - possible object breakup
- Increased risk of collision between two objects
- New launch and deployment of satellites
- Objects docking
- Objects separating
- Orbital decay and re-entry

There are two basic types of sensors, active systems such as radars, and passive systems such as telescopes. Radars generate pulses of radio frequency energy and listen for the echo returned from the satellite. Laser radars, or LIDAR, work in a similar way except that instead of radio frequency energy they transmit pulses of light using high power lasers. Telescopes view satellites at night using the Sun for illumination.

Future - January 2060

Future scenarios include all of the current day scenarios plus

- Intercontinental ballistic transport
- Lunar and Martian spaceflights

Data Formats

Current Catalog

The current catalog of satellites is provided by space-track.org and consists of Two Line Elementsets (TLEs). These are 80 column ASCII files that were originally punch card decks.

Satellites in the catalog are identified by a number, with the oldest in the catalog being object number 5, launched in 1958.

The format is defined on space-track.org and at Celestrak[4]

```
1     5U 58002B   20004.25808406 +.00000204 +00000-0 +25697-3 0  9997
2     5 034.2553 017.2404 1845519 328.9445 021.3764 10.84795732187314
1    11U 59001A   20004.92095594 +.00000281 +00000-0 +15460-3 0  9996
2    11 032.8685 313.1484 1467962 042.6596 327.9080 11.85649558255448
1    16U 58002A   20004.72847591 -.00000102 +00000-0 -16578-3 0  9996
2    16 034.2775 270.2215 2029024 263.2566 073.4538 10.48721322441543
```

There is also a 3 line element set (3LE) that adds a header line. Here's some recently launched SpaceX Starlink satellites

```
STARLINK-1073
1 44914U 20001A   20035.25001157 -.00053385  00000-0 -13733-2 0  9991
2 44914  53.0016 259.0209 0001278  82.3171 176.2246 15.38733438  4418
STARLINK-1084
1 44915U 20001B   20035.25001157  .00176809  00000-0  41119-2 0  9996
```

[4] https://www.celestrak.com/NORAD/documentation/tle-fmt.php

```
2 44915  53.0006 258.8546 0000985  82.6107  22.9537 15.41172422  4420
```

Observations

Ground-based radar observations have the form of time, range, range rate, azimuth and elevation angles, as well as an estimate of the size of the object. The range measures the distance from the observer to the satellite, the range rate measures how fast the satellite is coming towards or moving away from the observer, the azimuth is the angle along the horizon (north, east, south, west) and the elevation is the angle above the horizon (0 to 90 degrees). The estimated size of the object is given in terms of an area called the Radar Cross Section (RCS). Radars are generally calibrated using special satellites that are simple aluminum spheres[5]

Data from ground-based telescopes is similar to radar data but does not include range or range rate, just time, angles and intensity.

Satellite Data

There is other useful satellite data in addition to the orbital parameters found in the TLEs. This data includes the launch date, country of origin, name and other data. For this project we can represent this as a JSON object, that consists of key/value pairs.

For example

```
{
    “name”:”LCS-1”,
    “number”:1361,
    “country”:”US”,
    “launch”:”1965-034C”
}
```

The JSON format allows for a lot of flexibility, portability and is easily managed with Python and Javascript.

Satellite data for the current catalog is available from space-track.org in comma separated values (CSV) format. The data is referred to as the SATCAT. The columns are

- OBJECT_ID
- OBJECT_NAME
- NORAD_CAT_ID
- COUNTRY
- PERIOD
- INCLINATION
- APOGEE
- PERIGEE
- RCS_SIZE
- RCSVALUE
- LAUNCH
- COMMENT

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[5] https://space.skyrocket.de/doc_sdat/lcs-1.htm

Some example SATCAT data. Note the heliocentric orbit - an orbit around the Sun - for the Russian launch in 1965. The letters “R/B” stand for “rocket body”.


```
"1965-093B","SCOUT X-4 R/B","1739","US","99.21","59.71","787","655","MEDIUM","0","1965-11-19",""
"1965-093A","EXPLORER 30","1738","US","99.99","59.71","847","668","MEDIUM","0","1965-11-19",""
"1965-092D","SL-6 R/B(2)","1736","CIS","","","","","","0","1965-11-16","HELIOCENTRIC ORBIT (SUN)"
"1965-091A","VENERA 2","1730","CIS","","","","","","0","1965-11-12","HELIOCENTRIC ORBIT (SUN)"
"1965-089B","DELTA 1 R/B","1729","US","120.25","59.39","2266","1118","MEDIUM","0","1965-11-06",""
```


Operator Commands

Operator commands are the responses to events. Some of the commands are

- task sensors to collect additional data
- advise satellite operators to perform maneuvers
- generate various types of alerts including
  - satellite breakup
  - high risk of collision
- perform catalog maintenance actions including
  - re-tagging observations
  - create of new satellite identifiers.

The operator commands are implemented in JSON format and include the identify of the operator submitting the command, the time of the command as well as the command and all associated data.

For example, a breakup alert would look like

```
{
    “operator”:”TestOperator1”,
    “command”:”GenerateBreakUpAlert”,
    “timeOfBreakUp”:”05-jan-2020 22:10:32”,
    “locationOfBreakUp”:”7426.364,234.587,-875.103”,
    “parentObject”:37543,
    “debrisObjects”: [6456443455,4564454553,4234234234,435353555345]
}
```

Recommendations

The recommendation engine generates a set of pre-defined commands in response to events. This set consists of potential recommendations, each with a description of the rationale and a confidence value.

Using the example above, a recommendation could look like this

```
{
    “recommendationSetID”: 66575567,
    “recommendationTime”:”05-jan-2020 23:43:21”
    “recommendationNumber”,1,
    “recommendationRationale”:recommmendation66575567rationale.txt,
    {
        “command”:”GenerateBreakUpAlert”,
        “timeOfBreakUp”:”05-jan-2020 22:10:32”,
        “locationOfBreakUp”:”7426.364,234.587,-875.103”,
```

"parentObject":37543,
"debrisObjects": [6456443455,4564454553,4234234234,435353555345]
}
}

The recommendation rationale is contained in a human-readable file so that an operator can see the data behind the recommendation.

If an event generates multiple recommendations then they would be listed together. For example, if necessary, there might be additional recommendations for sensor tasking to find additional debris objects

Operator Interface

Initially the operator interface should be a simple display of status, upcoming scheduled events, alerts, along with recommendations and a means of submitting commands and accepting recommendations.

Recommendation Engine

Scenario 1: SSA Operator

A hypothetical Space Situational Awareness (SSA) Operator is tasked with monitoring data being received by a set of sensors that includes both radars and telescopes.

The SSA operator receives information from the sensors in the form of observations of objects in space. These observations consist of the time of the observation, the intensity or brightness of the observation, the angle from the sensor to the object and in the case of radars, the distance between the sensor to the object. Observations are correlated with a catalog of known objects and tagged with the identity of a known object if it meets certain criteria. In general the criteria for tagging an observation with the identity of a cataloged object is based on the difference between the observed position and the estimated position of the known object at the time of the observation.

When a sensor is scheduled to observe the pass of a known object and successfully collects observations on that object those observations are communicated to the SSA operations center.

A known object is generally referred to as a cataloged object, or Resident Space Object (RSO). When an object is observed and it is not a cataloged object it is referred to as an Uncorrelated Target, or UCT.

Some sensors have an ability to perform searches to find un-cataloged objects.Telescopes are generally used to search for deep space objects (those over 10,000 km above the Earth's surface) and certain types of radars are used to search for objects in space.

When a sensor is scheduled to observe the pass of a known object but for some reason does not observe the object this gets reported as a “Missed Pass”. There are a number of reasons why a sensor might not observe an object when scheduled. Some of the reasons for a failed pass include:

- Sensor problems: a malfunction at the sensor could cause it to fail to collect observations
- Weather: primarily an issue for telescopes, where clouds and rain will prevent it from making observations of satellites, but in some cases weather can reduce the sensitivity of radars to the point where it fails to detect small objects
- Satellite maneuver: the scheduled observation failed because the object has changed its orbit. In this case, the object may have been observed and categorized as an unknown object or UCT. If this is the case, then once the maneuver has been confirmed the UCT observations will be re-tagged with the RSO identifier and the RSO orbit will be updated.
- Satellite breakup: while rare, objects in space can break up, either as the result of an on-board explosion caused by batteries or fuel, or because of a collision with orbital debris. Debris created from this breakup may be observed as unknown objects or UCTs. If so, through orbital analysis it may be possible to determine if a debris object was created through the breakup of a known object.

Initial Demonstration

For the initial demonstration a stream of data that contains observations and missed pass messages will be sent to the SSA operator. This data will also be sent to the Recommendation Engine so that it can provide the operator with recommended Courses of Action (COA) for the various scenarios.

The simplest case is for sensor problems. When the sensor is providing observations on scheduled passes then misses more than one pass in a row, then the RE should alert the operator that there may be an unreported sensor issue. If any of the passes missed are priority targets then the RE may provide a recommendation for increased priority tasking on those objects.

More complex cases involve missed passes due to maneuvers or breakups. In these cases the RE searches for UCTs with orbital parameters similar to the missing RSO. In general, if the object maneuvers or breaks up then there will be a UCT (or multiple UCTs) with an orbit that differs from the RSO orbit by a velocity difference on the order of 10 to 1000 m/s.