SENSOR FUSION IN SPACE POPULATION MONITORING

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ABSTRACT

Because of the increasing population of space objects, it is important to optimise the use of space surveillance sensors. Until recently, most sensors used for non-LEO surveillance have been target-oriented tracking systems. We have investigated the application of a survey-only surveillance strategy and show that the fusion of tracking and surveying sensors has productivity advantages in a space surveillance network. We have implemented and put into operation a strategy demonstrator whose holistic system design tackles the cost problem associated with wide field of view optical sensors and which has demonstrated its ability to sample all non-LEO orbits.

1. INTRODUCTION

Optical sensors are commonly used for surveillance of the higher Earth orbits. Since 1957, such sensors have evolved from naked-eye kinetheodelites, through photographic and intensified TV systems, to CCD-based robotic sensor networks (King-Hele, 1966, 1992). To date, these have mostly been target trackers.

2. TRACKING SYSTEMS

As an example of a tracker, we consider the PIMS system – a UK government asset for the surveillance of space. The name (an acronym for Passive Imaging Metric Sensor) is derived from the sensor's exploitation of the passive illumination of space objects by the Sun (*cf.* active radar-like illumination) to show them against the background night sky.

Designed in 1995 and in operation since 1996, the PIMS network has five geographically-dispersed sensors and was probably the first fully robotic network of optical telescopes dedicated to space surveillance.

Each sensor is a commercial off-the-shelf (COTS) 40 cm aperture Schmidt-Cassegrain telescope housed within an astronomical dome; the imager is a thinned chilled 1k-x-1k CCD. The sensor uses low-cost mount and optics, and employs relatively conventional image processing algorithms. It tracks objects down to ~ 0.5 m in GEO and reports positions in J2000 right ascension and declination with an accuracy of < 2 arcsec (which is suitable for monitoring and catalogue maintenance).

Figure 1. The PIMS sensor (right) at the NERC Herstmonceux, UK, site.

A bespoke mount control system was retrofitted in 2000/2001; each axis now has a dedicated motion control processor and can slew at rates up to 5º per second thus enabling PIMS to track objects in GTO, MEO, and HEO orbits.

PIMS is a low cost system: its accuracy is obtained economically by using the background starfield as the calibrator instead of expensive mount encoders and the operational cost is minimised because the robotic sensors require no human operators.

The sensor has a relatively small field of view (0.6° x 0.6°) and this limits its surveying capability. However, while tracking one object, PIMS will detect all objects seen within its view and so it serendipitously catches passer-by objects.

3. CATALOGUE MAINTENANCE ISSUES

In general, tracking sensors have three significant problems because of their small fields of view.

First, surveying is very time intensive. To survey the GEO population to an inclination of 15° visible from one site would require about 10,000 sensor move-expose-process cycles; for a 30 second cycle duration, a one-pass survey would take nearly 100 hours of night observing (without any re-visits to found objects).

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Second, a small field of view makes very difficult guaranteeing null-finds within a survey area because objects can slip through the search pattern.

Third, for newly found objects, the short arc of orbit observed means that the initial orbit determined will be of poor quality; it is most unlikely that follow-up observing will locate the object again.

4. MONITORING ISSUES

For population monitoring (with a secondary debris detection role), searching must be practicable and follow-up observations must be successful.

Each instance of a follow-up failure generates two additional problems: sensor time has been wasted chasing after the 'no show' object, and the discovery observations are orphaned within the data processing/cataloguing process.

Escape-proof searches are essential for knowing (down to some size/albedo limit) that objects *are not present* within a given volume of orbit-parameter space. Such null-find information provides a foundation for future mission planning within an ITU context and for collision threat analysis.

Also, for known objects, there is a large range of desirable re-visit timescales. Passivated objects have orbits for which a long re-visit interval may be acceptable; close approach candidates and tightly-clustered active payloads may need tracking several times per night.

These issues impose significant constraints on sensor observing schedules which also have to be mindful of fixed topographical restrictions (such as mountain peaks or radio masts) and time-position variable restrictions (such as the Moon or bright planets which can blind the sensor). Thus it is difficult to provide appropriate surveillance coverage with a small number of tracking sensors; one might conclude that tracking sensors are good at observing known objects but of minimal value for general surveillance – the smaller the sensor's field of view, the truer this becomes.

5. TOWARDS SURVEILLANCE

We have investigated the utility of a wide field of view survey-only system which ignores the target-oriented philosophy of tracking and instead borrows from the continuous scan method common in air defence and marine radars. A scan works like a trawl-net for catching fish; the radar does not target specific objects but instead detects them when illuminated by its beam.

The key advantages of a wide field of view (4º x 4º) sensor result from the short time it takes to cover GEO – using only 200 move-expose-process cycles.

Thus new and known object re-visits are frequent and follow-up observations are taken automatically with the only restriction being that the object is still visible somewhere in the sensor's sky; there is no need to determine an initial orbit at discovery time. The follow-up hunting problem which plagues tracking systems is now replaced with a non-trivial but more solvable object/orbit correlation problem. By definition, sensor time is never wasted on 'no shows'.

Thinking about the problem of re-visit success in population monitoring, we introduce the notions of *adequate predictability* and *adequate identifiability*.

We define the former to mean that an object will, upon re-visit, be within a reasonable hunt area of its predicted position. Fig. 2 shows the angular prediction error (compared with observations) over 1,400 days for 1967-07-A and 1976-10-A and we would say these orbits (from a 60 day span) are adequately predictable; a tracking sensor would easily re-acquire these objects.

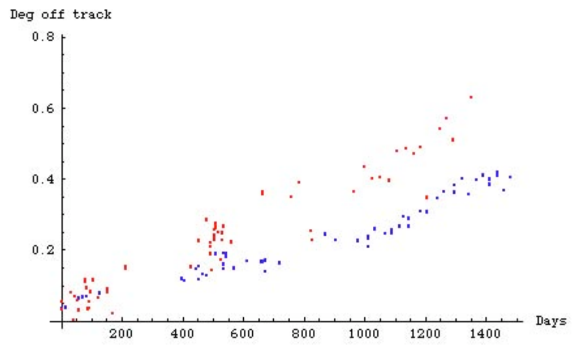

Figure 2. Degrees off track (O – C) over 1500 days for objects 1967-07-A and 1976-10-A

We define the latter to mean that an object, when re-observed, will be identified correctly. Fig. 3 shows the angular prediction error (compared with observations) for 1971-95-A over ~ 900 days.

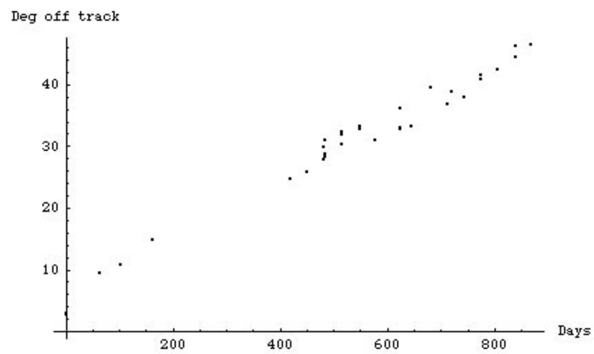

Figure 3. Degrees off track (O – C) over 900 days for object 1971-95-C

This orbit is only adequate for subsequent identification; a tracking sensor would fail to re-acquire this object but observations from a surveying sensor would be able to be correlated.

Another advantage of surveying is that multiple orbit families can be monitored simultaneously. For example, the typical GNS/MEO population overlaps with the GTO and GEO region on an all-sky view.

However, a significant problem with a survey-only strategy is cost. Large aperture optics which also have a wide field of view are expensive – as are the large CCD arrays (implemented as monoliths or mosaics) which are needed to cover physically large focal planes if normal image sampling rules are applied. The cost model is illustrated in Fig. 5, on which is marked various relevant sensor systems.

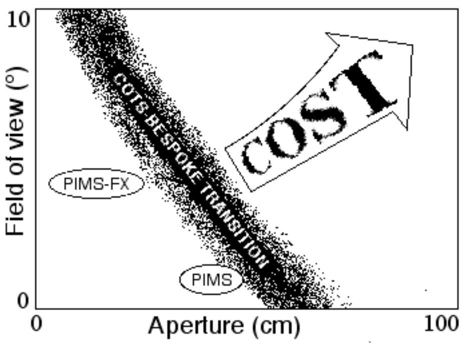

Figure 5. Cost in surveillance systems

Thus we looked at both these cost drivers and asked

- *how small is a sufficient aperture*? and
- *how under-sampled can the image be*?

6. PIMS-FX

Our strategy demonstrator is PIMS-FX, a Field eXtension variant of PIMS which was designed in 2003 *ab initio* as a survey instrument for space surveillance.

PIMS-FX has a tiny 10 cm aperture, a 3.8° field of view and ~1 m detection capability in GEO; the CCD sensor and other elements of the infrastructure are identical to those used on PIMS. The sensor is light weight (<10 kg) and can be co-mounted with PIMS to share the benefits of the bespoke mount control system. It uses image processing algorithms which avoid the sensitivity degradation of reference-frame subtraction techniques and which detect objects even if coincident with stars in an image. These algorithms make it ideally suited to the task of performing escape-proof surveys, and to null-find verification.

The survey rate is 1 sq^{o} per 10 seconds which translates into a payload scan of the GEO longitudes visible from a site every 75 minutes.

PIMS-FX is capable of detecting objects in GEO, GTO, MEO, and HEO orbital families. For example, Fig. 7 shows a high-eccentricity frozen-apogee (HEO) object and Fig. 8 shows GEO, MEO, and GTO objects.

Figure 6. PIMS-FX co-mounted with PIMS

7. RESULTS WITH PIMS-FX

PIMS-FX was used at the UK PIMS site for routine space surveillance work from late November 2004 to early February 2005 and has successfully met all of the demonstration goals.

During January 2005, good observations were obtained on ~70% of low-inclination payloads with altitudes greater than 15º; observations of close-clustered objects (*e.g.* Astra, HotBird, *etc*.) were later deleted by the data processing system to avoid wrong identification and account for 95% of the "missing" 30%.

In the same period, ~10% of the observations taken by the PIMS-FX sensor were uncorrelated with previously known objects. Subsequently, ~25% of those uncorrelated observations were successfully intra-correlated to give sets of observations spanning several days which could then be used for determining orbits.

8. OPTIONS

The survey rate is a near-linear function of the number of PIMS-FX sensors; to increase surveillance capacity, multi-sensor configurations can be used. The light weight of each PIMS-FX sensor head enables multi-head sensor swarms to be co-mounted within one domed building. Alternatively, by using, say, an octagonal building and multiple sensors on fixed mounts, a low-cost optical fence could be constructed with no moving parts.

The COTS approach used in PIMS-FX makes many-sensor clusters affordable. Using as a measure of cost effectiveness the combined cost of the optics, mount and detector per square degree of single-frame coverage gives k€6/sqº for PIMS-FX and k€248/sqº for PIMS.

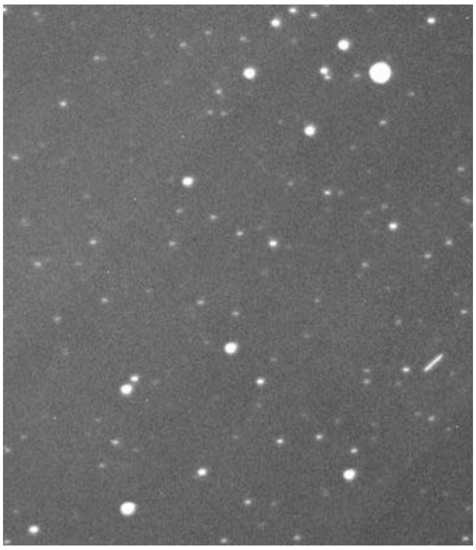

Figure 7. Part of PIMS-FX image showing trail of 1999-073-A, a HEO payload

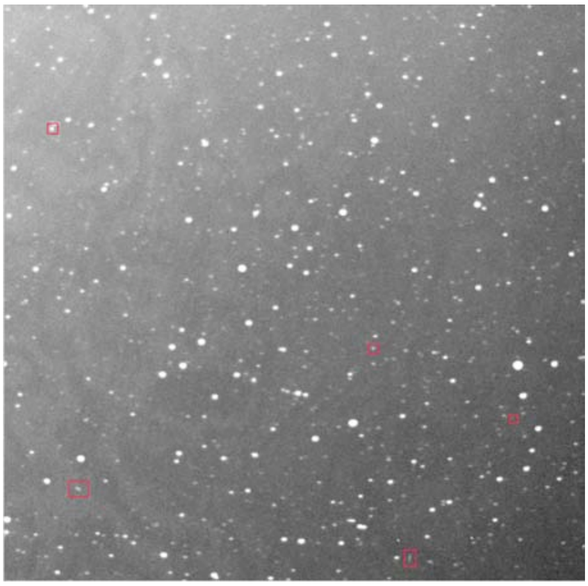

Figure 8. A PIMS-FX image showing GEO, GTO, and MEO payloads (boxed in red)

9. FUSION

PIMS-FX has been integrated into a network of sensors used for space surveillance.

The advantages of this integration include

i) higher availability of the tracking sensors because they are no longer used for surveys

ii) sensors with large apertures do not spend time tracking bright objects

iii) better orbit updates because more objects are re-observed more frequently

iv) automatic re-observation of discovered objects nights later allows good quality initial orbits to be determined

v) no programme of hunting/searching

vi) "no show" objects do not waste sensor time

vii) minimal sensor scheduling overhead

viii) simultaneous coverage of different orbital families

The PIMS-FX programme has successfully demonstrated that

a) small aperture optics and an under-sampling detector combined with the appropriate image processing algorithms can be used for general space population monitoring

b) changing surveillance method from tracking-oriented to survey-oriented delivers significant benefits in support of cataloguing both known and newly discovered objects

c) in a surveillance context, workload sharing between small and large aperture sensors can optimise sensor network productivity

and

d) low-cost but appropriately specified robotic sensors like PIMS-FX can easily augment a space surveillance network to provide weather and technical outage resilience.

Analysis of the observations taken during operational trials is continuing, funded by BNSC.

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