Autonomous spacecraft navigation using millisecond pulsars

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Overview

1. Project description
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1. Project description

I. Determine how accurate a spacecraft can determine its position autonomously
   - Need at least three different pulsars to determine position

II. Use pulsar as time reference
   - Periods ranging from ms to s
   - Spinning and highly magnetised neutron stars
   - Emits over a range of frequencies
   - At ~1400 MHz, the signal intensity rapidly decreases with frequency
1. Project description: Current techniques

Achieves ~ 1 meter and ~ 1 nanoradian uncertainty of plane of sky from Earth

- Uncertainty = How close the measurement is to the true position using Doppler ranging from Earth and delta differential one-way ranging (ΔDOR)

Two common ways to do it:

1. Optical methods, such as Deep Space 1 (DS1)
   - Determine source position by taking images of bright asteroids

2. X-ray pulsar navigation
   - Determine relative position through comparing ms pulsar signals with time references, as well as its phase lags
1. Project description: Challenge

- Can radio navigation do as well or better than X-ray navigation, but in smaller package?
  - Radio wave signatures are sharper in time
  - Better signal to noise ratio (SNR)
  - Better angular resolution
  - More pulsars than X-rays
1. Project description: How?

- Near ~1400 MHz, 20 MHz bandwidth of sky is reserved for radio astronomy

- Test the detection of a strong pulsar with the SRT
  - Crab pulsar (PSR B0531 + 21)
  - Measured at 16.6667 MHz bandwidth due to lack of storage

- In space, no bandwidth limit due to human communications

- With 16.6667 MHz on Earth, extrapolate the bandwidth to see how well the detection of pulsars will do in space
2. Data collection: SRT with SDR
2. Data collection: How much and why?

- Collected data from the Crab Pulsar using thor.py script
  - Integrated time: 1 hour
- Nyquist theorem: $f_{\text{nyquist}} = \frac{f_{\text{sampling}}}{2}$
- Sampled at 16.6667 MHz

$$16.6667 \, MHz = 16.6667 \, \frac{\text{Megasamples}}{\text{second}} \text{ at } 4 \, \frac{\text{bytes}}{\text{sample}} = 66.6667 \, \frac{\text{Megabytes}}{\text{second}}$$
3. Methods: Dispersion

- Know pulsar’s period as exactly as possible
  - Crab pulsar’s period: 33.3924123 milliseconds

- Dispersion measure
  - Way of quantifying # of electrons that the pulsar’s signal must travel through to reach the Earth
  - Radio signatures travels at different paths dependent on frequency

- Correct for dispersion (De-dispersion)
  - Divide wide receiver bandwidth into many individual channels
  - Subtract dispersion delay between channels
  - Sum channels to form an average of pulse profiles
3. Methods: Dispersion
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\[ Dispersion = \exp\left( i \frac{2\pi D \nu^2}{\nu_0 (\nu + \nu_0)} \right) \]

- \( D = \frac{Dispersion \; measure}{2.41 \times 10^{-4}} \)
- \( \nu = centre \; frequency \)
- \( \nu_0 = Subchannels \; of \; centre \; frequency \)
3. Methods: Folding

- Fold the data by pulsar’s period
  - The number of bins will be in the pulsar’s period
  - Stack pulsar’s period on top of each other
    - $1^{st}$ bin added to $1^{st}$ bin and etc
  - Summation of the stacks
  - Signals are in phase with each other, so peak will appear
  - Noise is not in phase
3. Method: Folding
4. What does the data tell us?

- Produces information on pulsar’s SNR
  - With SNR, can make a model that we can use to design a radio navigation system
  - In other words, what will the SNR be for:
    - Other (weaker) pulsars
    - Different dish sizes – and are they small enough for spacecraft? (Do we need to use advanced antenna designs such as folding antennas to get a size big enough?)
    - Different bandwidths
4. What does the data tell us?

- Phase (time of arrival)
  - Will tell us the distance if we have a very accurate clock
    - Accurate clock through astronomical masers
  - Clock should be occasionally updated by period and phase of pulsar
5. Results
5. Results

$Noise \downarrow$

$Expected \rightarrow$

![Graph showing noise decrease](image)
6. Conclusions / Further work

- Analyzed test data from a prototype pulsar detection system
- Determined minimum integration time with a SRT size antenna for pulsar detection
  - 1 Hour: Not enough data to see a pulse (even with folding)
  - Checked through two different analysis methods: same result
- Future
  - collect data for a much longer time than 1 hour to enable detection
  - Correct for motion of the observer due to rotation

Future applications:

- Masers to measure spacecraft’s velocity
- Masers to measure relative position of multiple spacecraft
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