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An Intelligent Decision-Making System for Flood Monitoring from Space

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Abstract

This paper presents the results of a feasibility study on intelligent image processing and decision-making for flood monitoring on board satellites. The ability to detect temporal changes in images is one of the most important functions in intelligent image processing systems for hazard and disaster monitoring applications. An automatic change detection system is proposed, the purpose of which is to monitor particular areas on Earth and give warnings to the authorities if any flooding events are detected. A novel solution to flood detection based on combined use of optical multispectral imagery and GPS reflectometry data is introduced. A fuzzy inference engine is used in the decision-making process, which generates control signals to other subsystems on board the satellite.

1. Introduction

Flooding is a disaster that occurs in many places on Earth. The main causes of flooding are heavy rain, hurricanes and undersea earthquakes. Heavy rain is the major factor of flooding, compared to the other two causes. Rain that falls in extended periods causes water from rivers to overflow and flood the nearby areas. Hurricanes destroy dams and levies, which results in heavy flowing of water. Undersea earthquakes can cause big tidal waves such as Tsunami, destroying and flooding coastal areas. The Tsunami disaster on Boxing Day 2004 [1] has led to human tragedy and loss of infrastructure on a very big scale. There are many ways to monitor and prevent flooding and satellite imagery has proven to be effective for monitoring flooding events.

Performing flood monitoring on board satellites is envisaged in future missions. However, current satellite design limitations and restricted on-board computing capabilities prevent such systems to be implemented yet. It is predicted that future satellite missions will be capable of carrying out intelligent on-board processing such as image classification, compression and change detection [2]. The ability to detect temporal changes in images is one of the most important functions in intelligent image processing systems for hazard and disaster monitoring applications. NASA's Earth Observing One Spacecraft (EO-1) carries several on-board science analysis experiments including cloud detection, flood scene classification and change detection [3]. In a related work, a specialized processor for on-board change detection is being developed for a repeat-pass change detection and hazards management [4].

This paper presents the results of a feasibility study on intelligent image processing and decision-making for flood monitoring on board satellites. An automatic change detection system for flood monitoring missions is proposed. A novel solution to flood detection based on combined use of optical multispectral imagery and GPS reflectometry data is introduced. A fuzzy inference engine is used in the decision-making process, which generates control signals to other subsystems on board the satellite. The paper is structured as follows. Section 2 reviews related work on intelligent image processing for satellite on-board use. Section 3 introduces the proposed intelligent on-board system. Performance evaluation results are discussed in section 4.

2. Related Work

Current commercial Earth Observation satellites have very restricted image processing capabilities on board. They mostly operate according to a 'store-and-forward' mechanism, where the images are stored on-board after being acquired from the sensors and are downlinked when contact with a ground station occurs. The implementation of high performance image processing on board satellites is a challenging task. On-board computer systems are embedded systems where power, resources and computer performance are a subject of constraints. Many factors have to be considered when deciding the type of hardware and software to be used on board a satellite. This section

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briefly reviews advanced image processing payloads of Earth observing small satellites [5].

Intelligent imaging capabilities have already been incorporated in several Earth observing satellite missions for experimental purposes. For example small satellites such as UoSat-5, BIRD and PROBA are carrying on-board experimental imaging payloads. The UoSAT-5 on-board imaging architecture is implemented on other SSTL satellite missions. For example, TiungSAT-1, which was launched in 1998 had two Earth Imaging Systems - Multi-Spectral Earth Imaging System (MSEIS) and Meteorological Earth Imaging System (MEIS). TiungSAT-1 carried two transputers (T805) with 20 MHz clocking speed and 4 MBytes SRAM as the processor for the EISs and was capable of autonomous histogram analysis ensuring optimum image quality and dynamic range, image compression, autonomous cloud-editing and high compression thumb-nail image previews.

The BIRD satellite that was developed by the German Space Agency is another small satellite with image processing on board. The imaging system of the BIRD satellite is based on two Infrared sensors and one CCD camera. Distinctive feature is the specialised hardware unit based on the neural network processor NI1000, which was integrated in the Payload Data Handling System (PDH) of the satellite. The PDH is a dedicated computer system responsible for the high-level command distribution and the science data collection between all payloads at the BIRD satellite. The neural network processor implements an image classification system, which can detect fire and hotspots.

The recent small satellite mission of the European Space Agency (ESA) Proba has advanced autonomy experiments on-board. The Compact High Resolution Imaging Spectrometer (CHRIS), an EO instrument, demonstrated on-board autonomy in terms of Attitude and Orbit Control System (AOCS) data handling and resource management. The images from CHRIS are processed in a DSP based Payload Processing Unit (PPU) operating at 20 MHz. The PPU provides 1.28 Gbit (164 MBytes) of mass memory and acts as the main processing block for all on-board cameras and other payload sensors.

A significant milestone with respect to on-board intelligent processing is the NASA autonomous Sciencecraft concept, which includes the development of the Techsat-21 satellite mission. The project also includes the development of on-board science algorithms such as image classification, compression, and change detection. Under this programme a specialized processor for change detection is being developed which is implemented on a multiprocessor system. The hardware is based on a hybrid architecture that combines FPGAs and distributed multiprocessors. Customised FPGA cards and high-speed multiprocessors are being developed because of the limited on-board memory (512 Mbytes or less) and the relatively slow processing speed of the current commercial-off-the-shelf (COTS) components. For the change detection task, the required processor performance is 2.4 GFLOPS and the required memory capacity is 4.5 GBytes. It is aimed that the multiprocessor card will have 4 to 8 GBytes on-board memory for the change detection processing task.

Table 1 illustrates the trend in image processing on-board small satellites in terms of functionality. It can be seen that more on-board image processing functions are included in future missions. This is made possible due to availability of more powerful computing resources on-board as shown in Table 2.

Table 1. Functionality trend in on-board image processing on small satellites

Satellite	Image Compression	Change Detection	Recognition and Classification
UoSat-5	Yes	No	No
BIRD	No	No	Yes
PROBA	Yes	No	Yes
FEDSAT	Yes	No	Yes
UK-DMC	Yes	No	No
X-SAT	Yes	Yes	Yes
Techsat21	Yes	Yes	Yes

Table 2. Computing characteristics of image processor payloads on-board small satellites

Satellite	Processors Speed	Main Memory (MBytes)	Parallelism
UoSat-5	20 MHz	4	No
BIRD	33 MHz	8	No
PROBA	20 MHz	128	No
FEDSAT	20 MHz	1	No
UK-DMC	100 MHz	1	No
X-SAT	266 MHz	64	Yes
Techsat21	133 MHz	128	No

3. An Automatic Flood Monitoring System on Board a Satellite

In this research we are concerned with implementing an on-board intelligent system, which can perform data processing and decision making before the data are transmitted to the ground stations. It is planned that the system can detect changes between two observation times and make decisions based on the information of the changes. The system is aimed at facilitating a flood-monitoring process using optical multispectral images.

Multispectral images are very attractive for use in flood monitoring analysis because of their low cost and availability. Currently synthetic aperture radar (SAR) images are widely used for flood detection and monitoring because of their capability to penetrate clouds, which can be heavy during flooding seasons. GPS information integrated with optical images can be used for image registration and identifying the reference image in the pre-processing subsystem.

For assessing the feasibility of this system, we use multispectral images taken from satellites in the Disaster Monitoring Constellation (DMC) developed by Surrey Satellite Technology Ltd. (SSTL). The areas to be monitored are fixed and the reference images are stored in an on-board database. The DMC images are similar to Landsat TM in terms of spectral and spatial resolution and are taken in Near-Infrared (0.76 µm to 0.9 µm), Red (0.63 µm to 0.69 µm), and Green (0.52 µm to 0.62 µm) bands. In the study, we also assume that the DMC satellite has a ground repeat track, which means that geo-rectification is not needed. We also assume that the sun illumination, atmospheric condition and other factors are the same with the ones in the database.

The conceptual outline of the proposed system is shown in Figure 1. The input of the system is a newly taken image from the imagers on board a satellite. The main blocks are: a pre-processing block, a database, a flood detection block and a fuzzy inference engine.

3.1. Pre-processing

The pre-processing block performs several critical tasks on the input image such as image tiling, image registration, change detection and cloud detection. In this conceptual design, an on-board database is introduced to store the reference image and other information that is useful for flood monitoring analysis, for example flooding historical data. Several image registration methods are tested to compare their performance, and the most optimal method is chosen as the method to be used in the proposed system. The experimental results are described in the next section.

3.2. Database

A hard disc data recorder (HDDR) based on a miniaturised hard drive device is planned to be used for the database. Hard disc drives are not common on board satellites and are still in an experimental stage. SSTL's Beijing-1 DMC satellite carries a pair of HDDRs, a 60 GB pressurized hard drive that can survive launch and the harsh space environment. Other than images, it is possible that the database stores dynamic weather data derived from ground databases, or possibly from meteorological satellites if there is a crosslink communication between them. The weather data can be useful to monitor flood and facilitate cloud detection algorithms included in the pre-processing subsystem.

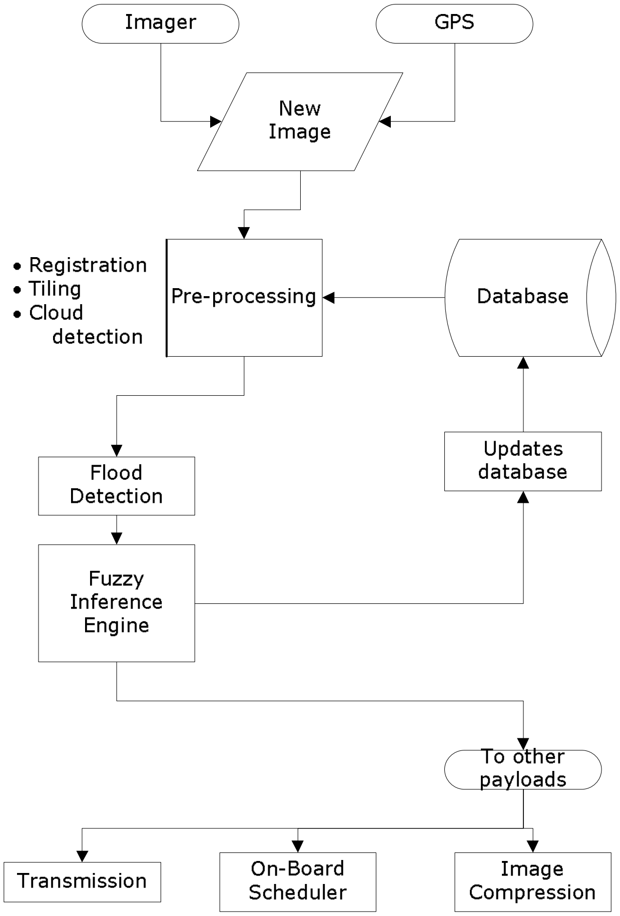


Figure 1: Block-diagram of the proposed automatic flood monitoring system

3.3. Flood Detection

The flood detection block is one of the main components of the system. Several flood detection algorithms were tested to evaluate their performance and the method that gave the most optimal results was selected as the method to be used on board. The output of this subsystem is a flood map image, which is to be used as an input to the fuzzy inference engine. The results of this performance evaluation are presented in the next section.

3.4. Fuzzy Inference Engine

As the flood detection processing block only produces a flood map image, a decision making block needs to be implemented. A fuzzy inference engine is introduced in the system as the decision-making block, the output of which will determine the next action of the system.

The reason to use a fuzzy inference engine is that it has the advantage of employing fuzzy membership functions, instead of crisp data. In the flood detection process the threshold that separates water and non water areas, T0, can be ambiguous. Using fuzzy logic reduces the errors caused by wrongly selecting T0. Figure 2 shows how the pixel values of the image are used as a membership function for the inference engine. The pixel values can be either water, ambiguous or non-water. If we were using T0 to threshold the pixels, some ambiguous pixels would be wrongly classified as water or non-water.

However, using fuzzy logic, ambiguous pixels can influence the flood detection results, not just the water and non-water pixels. The membership function will define how close the ambiguous pixels are to either water or non-water pixels. The output will not be just flooding or not flooding, but it will be in fuzzy sets, for example, “no alert”, “medium alert” and “high alert”, depending on the input, as shown in Figure 3.

Initially the output of the flood detection processing block was the only input to the inference engine. At this stage of the work, several other options of inputs to the inference engine are being tested to find their effectiveness against using flood detection alone. Other options of input data are summarized in Table 3. Connecting the input of the fuzzy inference engine straight to the pre-processing block is also tested to eliminate the processing of the flood detection algorithms described in Section 4.

Table 3: Inputs for the inference engine

N	Input data	Description
1	Pixel value of NIR/Red for tile 1 and 2	The rules will determine if each pixel is flooded or not.
2	Index for each tile	An index is calculated for each tile, so no pixel-to-pixel comparison.
3	Combination of input 2 above with GPS reflectometry	Same as above with added advantages of immunity to cloud cover
4	Frequency information of the tile (e.g. Fourier Transform for each tile)	Alternative way of processing instead of using spatial information.

3.5. Using GPS Reflectometry for Decision-Making

The third input design option for the fuzzy inference engine, using GPS reflectometry as shown in Table 3, is a novel work utilizing GPS reflection for remote sensing [6] on board satellites. Using GPS reflectometry has the advantage of having the ability to penetrate clouds, as opposed to optical imagery, and also they are cheaper and lighter than traditional SAR imagers. This is very useful for the small satellite platform. The potential of using this method for water detection is illustrated in Figure 4a and 4b [7]. As GPS signals travel across the surface they are detectable in Low Earth Orbit using a modified GPS receiver. As the signal traverses the surface it responds to surface features, including near surface water as demonstrated below. Concerning Figure 4 b, the Missouri river can be seen intersecting the line of reflection points at second 2 (corresponding to the sharp jump in power) and continuing into Omaha City. The spikes near the 12th and 15th seconds are probably due to the crossings of a Loup. It is also probable that the increase in signal power observed over this general region (between seconds 12 and 17), are due to the increased presence of water around the river’s present in these areas. A more detailed look at these areas would be needed before knowing for certain if the increased power levels were due to the presence of surface water.

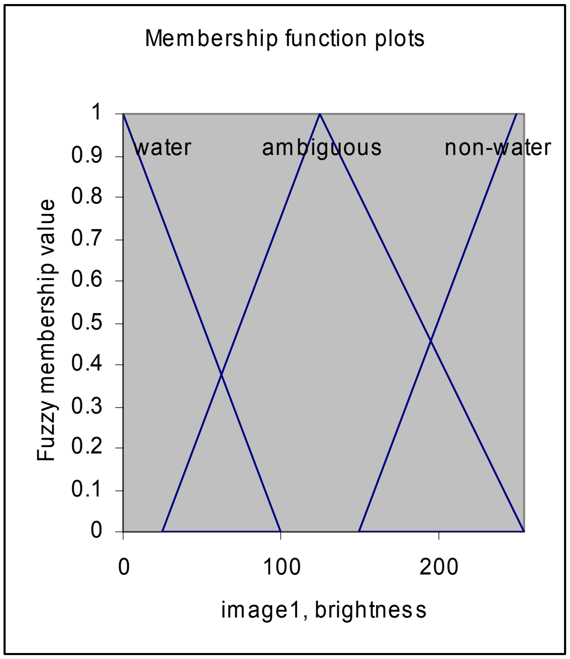


Figure 2. Membership function plots of the inference engine input

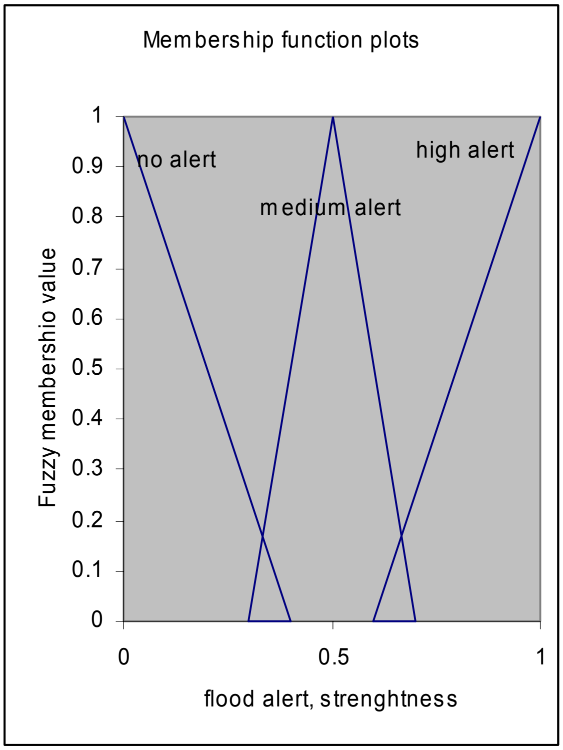
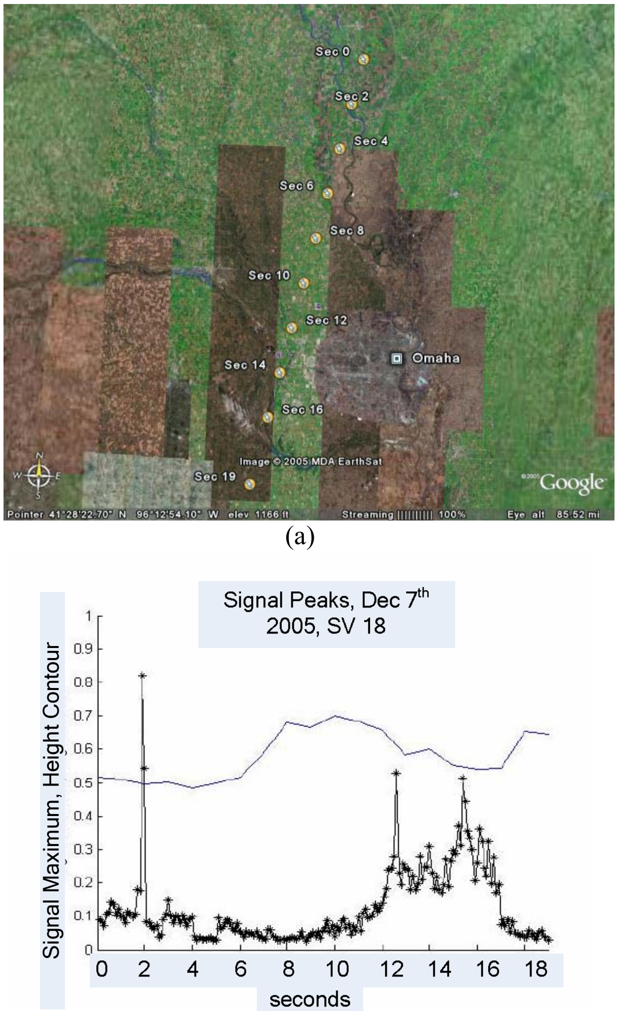


Figure 3. Membership function plots of the inference engine output



(a)

(b)

Figure 4. a) The path of a reflected GPS signal across 19 seconds of data. b) The peak power returned (with estimated height contour) over the entire data collection.(Image courtesy of GoogleEarth)

3.6. Alert to Trigger Other Events

The output of the fuzzy inference engine in Figure 1 is a flooding alert. The alert can be set into three types: low, medium and high (Figure 3). This will allow the system to trigger subsequent tasks such as image compression, warning alert or scheduling of other imaging tasks. For example, if the flooding alert is high, the system can send a high priority warning alert to the ground station.

4. Experimental Evaluation

In order to choose the optimal image registration and flood detection methods for the pre-processing block in Figure 1, several candidate methods were applied to two image sets as described in Table 4 [5]. The objective of this experiment is to find the processing speed and memory used for each methods for a given image size. On the DMC platform the software implementation of the system can be executed in the Solid State Data Recorder (SSDR) units. The PowerPC based SSDR unit is used for the performance evaluation presented in this section. The PowerPC processor is capable of executing 280 Dhrystone MIPS at 200 MHz and has 1 MByte of RAM. The software was executed on a Pentium M 1.3 GHz personal computer since flight test hardware was not available to use. In order to estimate the performance of the SSDR PowerPC the Dhrystone 2.1 benchmark program was run on the test Pentium computer resulting in 1665 Dhrystone MIPS. The experimental results were then scaled down to reflect the DMC SSDR performance, using the MIPS rate of the SSDR PowerPC processor.

Table 4: The multispectral image sets used for the performance evaluation

Before flooding	Date acquired	Source
1) North Sumatra, Indonesia	15 August 2001	Landsat7 ETM+
2) West Thailand	15 January 2002	Landsat7 ETM+
After flooding	Date acquired	Source
1) North Sumatra, Indonesia	4 January 2005	UKDMC
2) West Thailand	27 December 2004	UKDMC

Figure 5 and Figure 6 show performance measurement results for image registration and flood detection respectively. The results illustrated in Figure 5 are based on the pair of 500 x 500 pixel images in Table 5 for the two processors - the test processor (1665 MIPS) and the targeted processor (280 MIPS). The tested registration methods are:

(1) Phase Correlation.
(2) Cross Correlation.
(3) Mutual Information.
(4) Fourier-Mellin Registration.

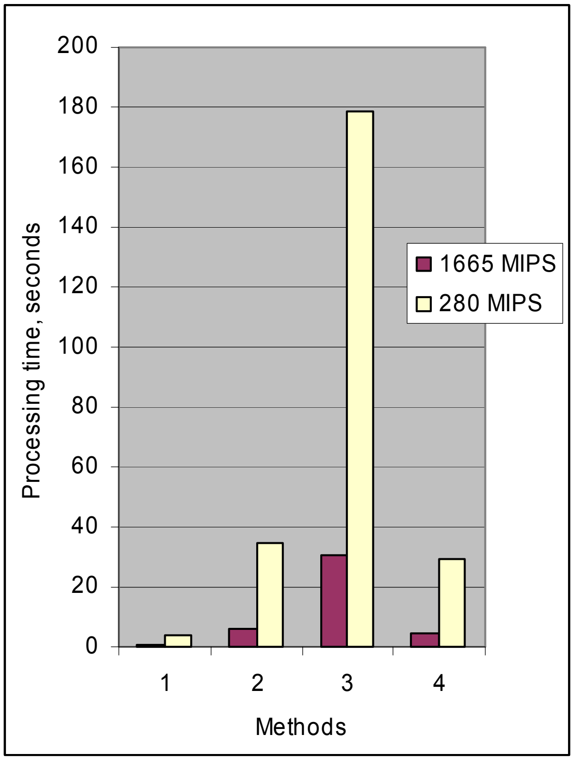


Figure 5: Estimated processing time of image registration methods

The results illustrated in Figure 6 are also based on the pair of 500 x 500 pixel images in Table 5 for the test processor (1665 MIPS) and the targeted processor (280 MIPS). The tested flood detection methods are:

(1) NDVI Differencing.
(2) NIR Band Differencing.
(3) Parallelepiped.
(4) Maximum Likelihood.
(5) Minimum Distance.
(6) Mahalanobis Distance.

The SSTL DMC images can have the maximum of 1200 image tiles of 500 x 500 pixels. So, the minimum total processing time to detect flood for 1200 tiles on a 280 MIPS processor (the target processor) can be estimated as follows:

Image Registration (Fourier Mellin)+Flood Detection
(NIR Band Differencing) =
= (29.26 + 0.24) x 1200 =
= 35400 sec = 590 minutes = 9.8 hours

The processing time of 10 hours is not acceptable for on-board implementation. In order to cut down the processing time, high performance computing capability is needed on board satellites, realized as a multiprocessor parallel architecture.

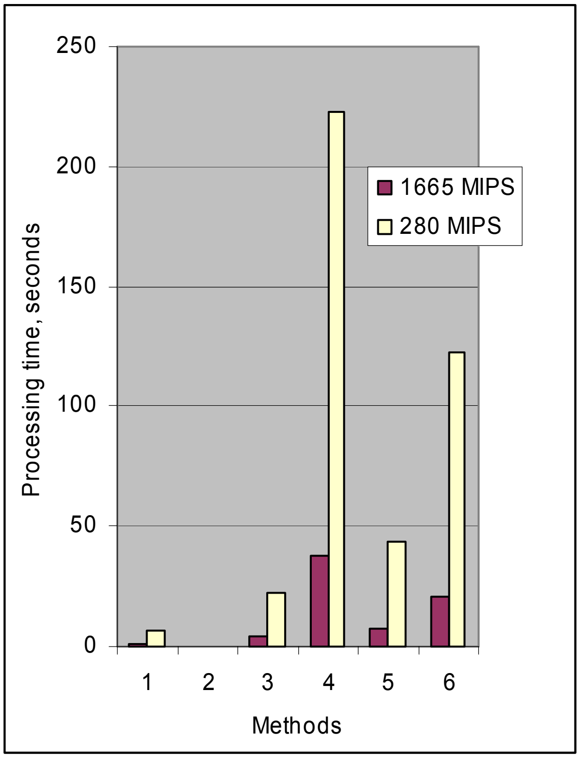


Figure 6: Estimated processing time of flood detection methods

5. Conclusions

This work investigates the possibility of using current image registration and flood detection methods for an intelligent decision-making system on board a satellite. Different than a conventional automatic flood monitoring system, this approach will process the multispectral images before they are being transmitted to the ground stations.

Several well-known image registration and flood detection methods were tested in order to find their expected performance on the computing hardware on-board a small satellite. A fuzzy inference engine is introduced to improve the flood monitoring performance. The evaluation study shows that it takes about 10 hours to process the maximum possible images that can be stored on-board a DMC satellite with the current computing capabilities. High performance computing on board the satellite is needed to cut down the processing time.

A novel solution to flood detection is proposed based on GPS reflectometry data. This technique could be used in conjunction with optical imagers to implement an efficient flood monitoring system on board a satellite. The GPS reflections ability to penetrate cloud cover will act as a valuable complement and backup for the flood maps produced by optical images.

The future direction of this research is to investigate the implementation of different input to the fuzzy inference engine, as well as to explore further the use of GPS reflectometry data with optical multispectral imagery.

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