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ABSTRACT

Fast variability of optical objects is an interesting though poorly explored subject in modern astronomy. Real-time data processing and identification of transient celestial events in the images is very important for such study as it allows rapid follow-up with more sensitive instruments. We discuss an approach which we have chosen for the RAPTOR project which is a pioneering close-loop system combining real-time transient detection with rapid follow-up. Our data processing pipeline is able to identify and localize an optical transient within seconds after the observation. We describe the challenges we met, solutions we found and some results obtained in our search for fast optical transients. The software pipeline we have developed for RAPTOR can easily be applied to the data from other experiments.

Keywords: optical transients, data mining, real-time software pipeline, robotic telescopes

1. INTRODUCTION

Over the last decade a substantial effort has been devoted to the development of astronomical optical telescopes capable of a rapid response to gamma-ray bursts detected by space borne instruments. A number of upper limits have been obtained in addition to the single truly spectacular discovery of a 9-magnitude optical flash associated with the GRB 990123, which was found to be at redshift z=1.6. This discovery has reaffirmed the importance of all-sky optical monitoring. There is an acute scientific need for an all-sky search and early detection of any unexpected events, including GRB optical counterparts and afterglows, supernovae, novae, dwarf novae, comets and asteroids, gravitational microlensing events and so on. Furthermore, about one million variable stars may be discovered and studied in detail with small wide-field optical telescopes by routine all-sky observations. There are several ongoing projects which image all the sky which is visible from a particular site every clear night and archive the data. However, none of these projects is able to detect an optical transient in real time because of the lack of adequate software. The wide field optical monitoring system RAPTOR (RAPid Telescope for Optical Response) is designed to identify and make follow-up observations of optical transients in real time. The most challenging aspect of the task is the development of a robust software able to do the job. In the following sections we briefly describe the project and discuss in more detail our software approach for the detection of optical transients in real time.

2. RAPTOR: FIRST CLOSED-LOOP SYSTEM FOR OPTICAL ASTRONOMY

The goal of the RAPTOR project is to detect an optical transient within a wide-field of view, identify it automatically in the real-time software pipeline, and perform follow-up observations with rapidly slewing narrow-field telescopes. More sensitive narrow-field telescopes will allow one to continue tracking the decline of an optical transient and to get its spectrum. To our knowledge this is the first experiment in optical astronomy which will be able both to detect optical transients automatically and in real-time, generate the alert and also to react on this alert for follow-up observations. To reach this ambitious goal we need to build the closed loop system which is schematically represented in Fig.1. Data acquisition, image registration, source extraction, transient identification, alert generation and telescope repointing are performed in real-time, before an optical transient is likely to fade out. For optical counterparts of gamma-ray bursts this means time scales on the order of one minute.

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The real-time hardware/software pipeline is currently under development for the RAPTOR project. The main components of the hardware are two identical systems, Raptor-A and Raptor-B, combining wide-field optical cameras with a more sensitive follow-up telescope. Data acquisition has been optimized for real-time transient detection as we discuss below. Image registration is performed as for other wide-field telescopes and is described in detail elsewhere. Source extraction is based on freeware tool SExtractor. SExtractor (Source-Extractor) is a program that builds a catalogue of objects from an astronomical image. It is particularly oriented towards reduction of large scale galaxy-survey data, but it also performs well on moderately crowded stellar fields. Both image registration and source extraction were significantly sped up for the real-time RAPTOR pipeline. Repointing of the telescope can be performed in record time by the unique mounting of the RAPTOR telescopes. Transient identification and alert generation blocks are critical for the operation of the whole pipeline and are newly developed for the RAPTOR project. So far the automatic detection of an optical transient has not been done for any astronomical project we are aware of. In the following sections we shall concentrate on these parts of the pipeline.

3. GENERAL APPROACH TO REAL-TIME DETECTION OF AN OPTICAL TRANSIENT WITH RAPTOR

The task of real-time transient detection has been successfully solved for X-ray all-sky monitoring about a decade ago. However, detection of an optical transient is a more challenging task. There are on the order of one hundred X-ray sources detectable in the whole sky by a modern X-ray monitor. In comparison, the number of objects for RAPTOR wide-field telescopes is measured by tens of millions. Many of these are variable sources which makes distinguishing them from optical transients more complicated. There are a lot of sources in the images which can imitate optical transients: flaring stars, comets, asteroids, meteorites, satellites, airplanes, hot pixels and image defects. Many false positives cannot be distinguished from the event of interest based on a single image only. This makes the use of an additional information essential.
However, our knowledge of the optical counterparts of gamma-ray bursts is limited. So far, only one event has been observed. What we expect to see is an optical flash from “empty” region of the sky which fades out on time scale of few minutes. To know which areas of the sky are “empty” we need to compare current observation with previous observations of the same field, either in the form of an image or as a source catalog. To be able to detect a variation we need to have at least two, ideally three, consecutive images of the same field. The expected time scales for variability of GRB optical counterparts are order of one minute, which dictates that a single exposure should be shorter than this time. But as we discussed above a single exposure is not enough. So we designed an observational sequence, which consists of multiple consecutive 30-sec exposures of the same field in the sky. As the distribution of GRBs is isotropic the probability of detection for a GRB optical counterpart depends on the size of telescope field-of-view and is independent from the pointing direction. However, we should try to avoid crowded fields in the Galactic plane where the effective area of “empty” regions is limited by the abundance of known sources. Visibility constraints dictate the choice of the field close to the zenith direction.

Another important feature of RAPTOR project is stereo observations of the same field in the sky. This is achieved by having two separate optical systems (Raptor-A and Raptor-B) with a separation of about twenty miles between them. This approach allows us to exclude all local objects contributing to false positives from the analysis. Comparison of two simultaneous observations with two different instruments will allow one to reduce the number of hot pixels among the false positives. To reduce the number of matched hot pixels in consecutive observations with the same telescope we apply dithering of the pointing direction, i.e. the center of the field of view is shifted by a fraction of a degree for two consecutive observations of the same sky field.

4. CATALOG

To understand what objects are “new” in the image one should use the information from previous observations. In the RAPTOR pipeline we compare the new source list with the catalog of known sources and weed out matches. The approach is quite obvious, but its implementation is a bit trickier. First you would like to have a
catalog which is complete for the sensitivity limit of the RAPTOR telescopes, but does not contain too many fainter sources, which would reduce an affective area for a transient detection. Also, available astronomical catalogs are static (i.e. lack time dimension). As a result they do not include many objects which demonstrate dramatic variability like novae, pulsating and cataclysmic variables. We tested the use of the GSC (Guide Star Catalog, see Fig.2) with ROTSE data and found that even though the limiting sensitivities are comparable, many ROTSE sources were unmatched in the GSC. More promising is the use of an updateable self-produced catalog obtained with the same instrument based on the results of previous observations. In this case we start from the GSC and expand it with objects matched in consecutive RAPTOR observations. This approach has been successfully tested with ROTSE data.

An important parameter is match radius, i.e. the maximum difference in coordinates of two objects detected in two different observations which are still considered to be the same source in the sky. To define this parameter for ROTSE test data we have obtained the distribution of the distance to the nearest neighbor (Fig.3). Two components, one composed of identical sources detected in two separate observations and the other which consists of random coincidences are easily distinguished. The exact choice of match radius depends on how many false positives you allow to be kept and what percentage of real matches you allow to be rejected.

5. IMAGE QUALITY CHECKS

An essential component of a fully automatic system for optical transient detection is an image quality check which allows one to exclude from the analysis the images which have substantial defects due to weather conditions during the observation, or malfunction of some hardware components. We developed several simple checks based on empirically found differences between good and bad images which could be easily included into the real-time analysis. Fig.4 illustrates one of the checks. For each test image we calculated the number of the detected sources and their mean magnitude for a given field. We accepted images which lie close to the straight
Figure 4. Dependence of mean magnitude of the detected sources on their number. Each diamond represents one test image of the same field. We found empirically that most of the good quality images lie along the straight line in logarithmic AI scale. We accepted the images which lie within the two dashed lines and rejected outliers.

It is also important in automatic image analysis, especially when you would like to detect source variability, to reconstruct reliably the brightness of each source. However, the measured magnitude of the sources is affected not only by the quality of the whole image but also by local image defects, which are particularly important for wide-field telescopes where separate parts of the field of view may have very different seeing conditions. To correct for local defects we have used a relative photometry method. The idea of this method is to compare the mean measured magnitude for a large group of closely located sources with the same value for the same group of sources from a standard image or source catalog. Significant deviation of the mean measured magnitude from the nominal value indicates that there is some problem with this part of the image and the magnitude of each source in the region needs to be corrected. In the case of a large value of the deviation for the whole image or large part of the image, this image or part of the image should be excluded from the analysis.

The result of the application of automatic image quality checks and relative photometry correction to ROTSE observations is shown in Fig.5. Diamonds represent the published light curve of variable star discovered by ROTSE. The data have been selected and corrected by a human expert in this case. Crosses are obtained from a larger dataset completely automatically with the application of image quality checks and the relative photometry correction.

6. ALERT GENERATION

Fig.6 shows the scheme of alert generation for the RAPTOR system. The alert generation is optimized for the search of optical counterparts of gamma-ray bursts. We observe the same area of sky with two identical wide-field telescopes installed in two separate positions (with a separation of about 20 miles between them).
Figure 5. Folded light curve of a variable star obtained with human screening of images (diamonds) and by application of automatic image quality control criteria and photometry correction developed for RAPTOR pipeline (crosses). The diamonds are shifted along vertical axis for clarity. The crosses are obtained from an analysis of larger set of observations.

The duration of each exposure is 30 s. The images are analyzed and a list of detected objects is built for each exposure. The two lists are matched, and a list of matches is produced. At this stage we reject hot pixels, image defects and local objects, which will have significant parallax in the images obtained from the two telescopes. Next we compare results from two consecutive exposures which allows one to eliminate random coincidences in the images. A new list of matches is compared with the previous exposure. If the object was present in the previous exposure then it is not a new object for exposure $n$ and should be rejected from the list of potential alerts. Comparison to the catalog allows one to eliminate constant and slowly variable sources which for whatever reason may not be detected in the exposure $(n-1)$. If the list of potential alerts is not empty after the completion of this procedure then an alert is generated and the source will be observed with more sensitive follow-up telescopes to follow its evolution.

7. TEST RESULTS

We have tested the algorithm of optical transient detection described above with the sequence of ROTSE-I data. ROTSE-I telescopes are similar to the wide-field telescopes of the Raptor-A and Raptor-B systems. However, the observational sequence has not been optimized for the search of optical transients according to our method. Using these data we could not expect to detect any fast optical transients, only long-living transients which are bright for time scales longer than a day. Of course, we could not utilize simultaneous observations of the same field with two different telescopes which is an unique capability of RAPTOR system. Still the results were quite promising. We have been able to suppress the rate of false positives down to 1 per 50 observations. This rate may be acceptable for internal alerts already, but we expect that using stereo observations we shall be able to eliminate most of the remaining false positives. The typical false positive during our tests was a very faint source which barely exceeds the detection limit and so was not included into the catalog. By random coincidence a hot pixel overlaps the position of this source in one of observations. As a result we detect a strongly variable source in two consecutive exposures and generate the alert. Another type of false positive is random coincidence of
Figure 6. Alert generation for an optical transient found with the RAPTOR pipeline. Two identical systems, Raptor-A and Raptor-B, observe the same sky field from two different locations on the ground. Images are analyzed and object lists are generated each 30 s. The sources in the object lists are matched for the two lists obtained from different telescopes. Then the lists for two consecutive exposures are matched. The matched sources in two consecutive exposures (n and n+1) are compared with previous exposure (n-1) and with the catalog of previous observations. If the source present in exposures n and (n+1), but was not detected neither in previous exposure, nor in the catalog of previous observations, an alert is generated.
two different hot pixels. The number of these and similar false positives will be further significantly reduced in stereo RAPTOR observations.

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REFERENCES