Real-Time Detection of Optical Transients with RAPTOR

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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 developed for the RAPTOR project, a pioneering closed-loop system combining real-time transient detection with rapid follow-up. RAPTOR's data processing pipeline is able to identify and localize an optical transient within seconds after the observation. The testing we performed so far have been confirming the effectiveness of our method for the optical transient detection. 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 a single truly spectacular discovery, a 9-magnitude optical flash\(^1\) 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\(^2\) and early detection of unexpected events, including GRB optical counterparts and afterglows, supernovae, novae, dwarf novae, comets, asteroids, gravitational microlensing events and more. Furthermore, about one million variable stars could be discovered and studied in detail by routine all-sky observations with small wide-field optical telescopes. There are several ongoing projects which collect and archive the images for all the sky visible from a particular site every clear night.\(^3\)-\(^5\) 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\(^6\)) is designed to identify and make follow-up observations of optical transients in real time. The most challenging aspect of the task has been 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 by the real-time software pipeline, and perform follow-up observations within the rapidly slewing narrow-field telescopes. “Zoological” abbreviation of the project emphasizes the concept of a system which is built as the analogy to biological vision systems. Transient events are detected with a wide-field telescopes which imitate peripheral vision. For the follow-up observations the transient is moved within field-of-view of narrow-filed telescopes imitating fovea. Two fovea cameras mounted on the common platform with wide-field instruments and separate spectroscopic telescope will allow to track the decline of an optical transient and to obtain 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 react to this alert for follow-up observations. To reach this ambitious goal we need to build the closed loop system 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 testing for the RAPTOR project. The main components of the hardware are two identical systems, Raptor-A and Raptor-B, combining wide-field optical cameras (19 x 19 square degrees field-of-view) with a more sensitive follow-up telescope (2 x 2 square degrees, limiting magnitude m=17).\textsuperscript{8} Data acquisition has been optimized for real-time transient detection as discussed below. Image registration is performed as for other wide-field telescopes and is described in detail elsewhere. Source extraction is based on freeware packet SExtractor.\textsuperscript{7} 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 done extremely quickly due to the unique mounting of the RAPTOR telescopes capable of slewing at a speed of about 100 degrees/s and accelerating to this velocity in less than one second.\textsuperscript{8} 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 by any astronomical project we are aware of. In the following sections we shall concentrate on these parts of the software pipeline.

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

The task of real-time transient detection was successfully solved for X-ray all-sky monitoring about a decade ago.\textsuperscript{9} However, detecting 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 obtainable by the RAPTOR wide-field telescopes is measured in the tens of millions. Many of these are variable sources, that are difficult to distinguish from optical transients. 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 can not be distinguished from the event of interest based on a

![Flowchart of RAPTOR project](image_url)
single image only. This makes it essential to use additional information, such as previous observations, parallax measurements with the second telescope, matching objects in consecutive observations etc.

Our knowledge of the optical counterparts of gamma-ray bursts is limited. So far, only one event has been observed. What is expected is an optical flash from an “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 a source catalog. To be able to detect a variation we need to have at least two, or better 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 have 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 the RAPTOR project is stereoscopic 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 38 km 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.

Figure 2. Magnitude distribution of sources detected in a single image with RAPTOR wide-field camera (camera C on Raptor-A system, 60 s exposure of the field of Regulus). For comparison the magnitude distribution of sources in Guide Star Catalog is shown (dashed line). Completeness limit is around m=13 for GSC.
Figure 3. Distribution of number of detected sources versus the distance to the closest match. Thin grey line shows random distribution of sources, solid histogram represents experimental data for two ROTSE observations of the same field. Rapidly declining component on the left is composed of identical sources, detected in both observations, broad component are random coincidences.

4. CATALOG

To understand which objects are "new" in the image, the system 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 need 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,\textsuperscript{11} with ROTSE (Robotic Optical Transient Search Experiment) data and found that even though the limiting sensitivities are comparable, many ROTSE sources were unmatched in the GSC (see Table1). 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 observations. This approach has been successfully tested with ROTSE data. For RAPTOR wide-field cameras most of the sources are expected to be present in GSC (see Fig.2), but for more sensitive fovea cameras just small fraction of the detected sources can be found there. In the RAPTOR project we will keep and update both more shallow catalog for wide-field cameras and deeper catalog for follow-up fovea observations. We expect that the former catalog will contain on the order of a million objects while the latter one may eventually include as many as 50 million objects.

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
Figure 4. Dependence of mean magnitude of the detected sources on their number. Each diamond represent one test image of the same field. We found empirically that most of the good quality images lie along the straight line in logarithmic Al scale. We accepted the images which lie within the two dashed lines and rejected outliers.

many false positives you allow to be kept and what percentage of real matches you allow to be rejected.

Updateable source catalogs from the RAPTOR observations will play important role in the real-time detection of optical transients. Also they will allow more detailed variability studies for large group of interesting objects and will supply the information for SkyDOT sky database.

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 line in this plot and rejected outliers, which appeared to have significant image defects. In our analysis we also filtered the images according to the total number of detected sources and percentage of the sources matched with the catalog.

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 use a relative photometry method. The idea is to compare the mean measured magnitude of a large group of closely located sources, with 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 deviation for the whole image or a large part of the image, then this image or part of the image should be excluded from analysis.

The result of the application of automatic image quality checks and relative photometry correction to ROTSE observations is illustrated in Figs. 5 and 6. Fig. 5 represents the light curve for a variable star produced by automatic RAPTOR pipeline. Fig. 6 shows the same light curve but obtained with automatic image quality checks and relative photometry correction included into the pipeline. For comparison we also show the light curve for the same variable star produced by a human expert. The comparison shows that quality of the data produced by the RAPTOR pipeline is comparable with the results of data analysis performed by the scientist.

6. ALERT GENERATION

Fig. 7 shows the scheme of alert generation by the RAPTOR system. The alert generation is optimized for the search of optical counterparts of gamma-ray bursts. The same area of sky is observed with two identical wide-field telescopes installed in two separate positions (with a separation of 38 km between them). The duration of each exposure is 30 s. Pointing direction slightly changes (dithers) between the exposures. Each image is analyzed immediately after its acquisition and a list of detected objects is built for each exposure and each camera. The list obtained with Raptor-A is compared with the list of objects from Raptor-B image, and a list of matches is produced. At this stage most of the hot pixels, image defects and local objects, which will have significant parallax in the images obtained from the two telescopes, are rejected. 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, (n-1), which has been analyzed at the previous step of the procedure. If the object was present in the (n-1) list of matches 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 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 step then an alert is generated and the source will be observed with more sensitive follow-up telescopes to follow its evolution down to about 17th magnitude and
Figure 6. Folded light curves for the same variable star as shown in Fig.5. Diamonds represent data obtained by human screening of images. Crosses are produced by the RAPTOR pipeline with application of automatic image quality control criteria and relative photometry correction. The diamonds are shifted along vertical axis for clarity. The crosses are obtained from an analysis of a larger set of observations.

improve the localization of the object from fraction of arc minute for initial detection with a wide-field camera to few arcsec for follow-up observations with fovea telescopes.

7. TEST RESULTS

The algorithm of optical transient detection has been coded in the C computer language and tested under Linux operational system 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 we have used in the testing 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 (see Table I for more details).

This rate may be acceptable for internal alerts, 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 two different hot pixels. The number of these and similar false positives will be further significantly reduced in stereo RAPTOR observations. During the tests on standard commercially available PCs the pipeline has been able to process the data in a rate sufficient for real-time processing of the RAPTOR data.
Figure 7. 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.
Table 1. Reduction of number of false positives in the test data by application of different filtering criteria (representative numbers for a sequence of testing images)

| Filtering criteria                                      | Average number of objects / image |
|---------------------------------------------------------|---------------------------------|
| Initial image (no filtering)                            | 15,500 objects / image           |
| Matching with GSC                                       | 2,600 unmatched sources / image  |
| Matching with internal updateable catalog               | 460 unmatched sources / image    |
| Pair matching of sources in consecutive images          | 85 false positives / image       |
| Ditherings between observations                        | 0.7 false positives / image      |
| Brightness level trigger (13th magnitude min)           | 0.02 false positives / image     |
| Stereoscopic observations                               | not tested yet                   |

8. CONCLUSION

We have designed and developed a software pipeline for a real-time detection of astrophysical transients in optical observations. The pipeline has developed for the RAPTOR project which is the first closed-loop system for optical astronomy combining real-time transient detection with rapid follow-up capabilities. The testing of the pipeline with ROTSE data has confirmed that our approach can be effective for the search of optical transients. Applying various filtering criteria we were able to reduce the number of false positives for transient alerts by several orders of magnitude. We also demonstrate that automatic image quality checks and relative photometry corrections can be applied with the pipeline to obtain automatically the results suitable for scientific data analysis. Quality of these results is comparable with the performance of a human expert. The speed of the pipeline is adequate for the processing of the RAPTOR data in real-time and generate alerts within 1 minute after the data acquisition.

We plan to perform a full-scale testing of the pipeline with the RAPTOR data in the coming months.

ACKNOWLEDGMENTS

Internal Laboratory Directed Research and Development funding supports the RAPTOR project at Los Alamos National Laboratory under DoE contract W-7405-ENG-36. Los Alamos National Laboratory is operated by the University of California for the National Nuclear Security Administration (NNSA) of the U.S. Department of Energy and works in partnership with NNSA’s Sandia and Lawrence Livermore national laboratories to support NNSA in its mission. This research has made use of data provided by ROTSE\(^1\) robotic telescopes.

REFERENCES

1. C. Akerlof, R. Balsano, S. Barthelemy, J. Bloch, P. Butterworth, D. Casperson, T. Cline, S. Fletcher, F. Frontera, G. Gisler, J. Heise, J. Hills, R. Kehoe, B. Lee, S. Marshall, T. McKay, R. Miller, L. Piro, W. Priedhorsky, J. Szymanski, and J. Wren, “Observation of contemporaneous optical radiation from a gamma-ray burst,” *Nature* 398, pp. 400–402, 1999.
2. B. Paczynski, “Monitoring all sky for variability,” *The Publications of the Astronomical Society of the Pacific* 112, pp. 1281–1283, 2000.
3. C. Akerlof, S. Amrose, R. Balsano, J. Bloch, D. Casperson, S. Fletcher, G. Gisler, J. Hills, R. Kehoe, B. Lee, S. Marshall, T. McKay, A. Pawl, J. Schaefer, J. Szymanski, and J. Wren, “ROTSE all-sky surveys for variable stars. I. Test fields,” *The Astronomical Journal* 119, pp. 1901–1913, 2000.
4. H.-S. Park, E. Ables, S. Barthelmy, D. Scott, R. Bionta, L. L. Ott, E. Parker, and G. Williams, “Instrumentation of LOTIS – Livermore Optical Transient Imaging System: a fully automated wide-field-of-view telescope system searching for simultaneous optical counterparts of gamma-ray bursts,” in *Optical Astronomical Instrumentation*, S. D’Odorico, ed., *Proc. SPIE* 3355, pp. 658–664, 1998.
5. G. Pojmanski, “The all sky automated survey,” *Acta Astronomica* **47**, pp. 467–481, 1997.

6. W. Vestrand, K. Borozdin, S. Brumby, D. Casperson, E. Fenimore, M. Galassi, G. Gisler, K. McGowan, S. Perkins, W. Priedhorsky, D. Starr, R. White, P. Wozniak, and J. Wren, “Searching for optical transients in real-time: the RAPTOR experiment,” in *Gamma-Ray Bursts and Afterglow Astronomy*, D. Kocevsky, F. Ryde, M. Boettcher, and I. Smith, eds., *Proc. of the Woodshole GRB Conference*, 2002 (in press).

7. E. Bertin and S. Arnouts, “SExtractor: Software for source extraction,” *Astronomy and Astrophysics Supplement* **117**, pp. 393–404, 1996.

8. J. Wren, K. Borozdin, S. Brumby, M. Galassi, K. McGowan, D. Starr, W. Vestrand, R. White, and P. Wozniak, “A distributed control system for rapid astronomical transient detection,” in *Advanced Global Communications Technologies for Astronomy*, *Proc. of SPIE* **4845-21**, 2002 (this conference proceedings).

9. S. D. Barthelmy, T. Cline, N. Gehrels, T. Bialas, M. Robbins, J. Kuyper, G. Fishman, C. Kouveliotou, and C. Meegan, “BACODINE: The real-time BATSE gamma-ray burst coordinates distribution network,” in *Gamma-Ray Bursts*, G. J. Fishman, ed., *AIP Conference Proceedings* **307**, p. 643, 1994.

10. C. Meegan, G. Fishman, R. Wilson, J. Horack, M. Brock, W. Paciesas, G. N. Pendleton, and C. Kouveliotou, “Spatial distribution of gamma-ray bursts observed by BATSE,” *Nature* **355**, pp. 143–145, 1992.

11. B. Lasker, C. Sturch, B.J., J. Russell, H. Jenkner, and M. Shara, “The Guide Star Catalog. I - Astronomical foundations and image processing,” *Astronomical Journal* **99**, pp. 2019–2058, 2173–2178, 1990.

12. P. Wozniak, K. Borozdin, M. Galassi, W. P. D. Starr, T. Vestrand, R. White, and J. Wren, “Virtual observatory for variable stars study,” in *Virtual Observatories*, *Proc. of SPIE* **4846-25**, 2002 (this conference proceedings).