Improving Software Development Management through Software Project Telemetry

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Abstract

Software project telemetry is a new approach to software project management in which sensors are attached to development environment tools to unobtrusively monitor the process and products of development. This sensor data is abstracted into high-level perspectives on development trends called Telemetry Reports, which provide project members with insights useful for local, in-process decision making. This paper presents the essential characteristics of software project telemetry, contrasts it to other approaches such as predictive models based upon historical software project data, describes a reference framework implementation of software project telemetry called Hackystat, and presents our lessons learned so far.

1. Introduction

It is conventional wisdom in the software engineering research community that metrics can improve the effectiveness of project management. Proponents of software metrics quote theorists and practitioners from Galileo's "What is not measurable, make measurable" [6] to DeMarco's "You can neither predict nor control what you cannot measure" [4]. Software metrics range from internal product attributes, such as size, complexity, and modularity, to external process attributes, such as effort, productivity, testing quality, and reliability [5].

Despite the potential of metrics in theory, effectively applying them appears to be far from mainstream in practice. For example, a recent case study of over 600 software professionals revealed that only 27% viewed metrics as "very" or "extremely" important to their software project decision making process [10]. The study also revealed that cost and schedule estimation was the only use of metrics attempted by a majority of respondents.

At least two hypotheses could account for the gulf separating the theory from the practice of software metrics. The first is that three quarters of practitioners are just plain uninformed: if they would subscribe to the journals and/or partake of the many educational opportunities regarding software metrics, they would immediately implement current "best practice" that would just as quickly improve their project management decision making.

While all of us, theorists and practitioners alike, can always benefit from additional reading and education, there is an alternative explanation. Perhaps the metrics methods used by theorists yield results not easily translated into practice? Consider that much metrics research involves the following basic method: (1) collect a set of process and product measures (such as size, effort, known defects, complexity, etc.) for a set of completed software projects; (2) generate a model that fits this data; (3) claim that this model can now be used to predict characteristics of future projects. For example, a model might predict that a future project

of size S will require E person-months of effort; another that the future implementation of a module with complexity C will be prone to defects with density D.

Practitioners face several barriers to adoption of these predictive, model-based approaches to metrics. First, to use the model unchanged, practitioners must confirm that the set of projects used to calibrate the model are similar to their own. This is the *Context Problem*: unless the context associated with the software process and project data in the repository is similar to the context associated with the practitioner's projects, then the applicability of the model's outputs to the practitioner is in question. Second, practitioners must also confirm that the context of their future projects will remain similar to their previous ones. If those two conditions cannot be met, then the model cannot be used without recalibration. This involves replicating the model-building method within the practitioner's organization, with the risks that the resulting model will not work or that the organization may change, rendering the context of future projects different from those used to calibrate the model. Third, they must assess the cost associated with metrics collection and analysis, and ensure that these costs are balanced by the relevance of the metrics and their interpretation.

Faced with these barriers, it is no wonder that many practitioners find it daunting to apply metrics best practices to their own situation. Indeed, the agile community generally argues against model-based metrics applications, promoting much "softer" metrics for decision-making [2].

Fortunately, creation of predictive models based upon historical project data is not the only possible way to apply software metrics to project management. In this paper, we present a new approach based upon the notion of "telemetry".

2. Software Project Telemetry

According to Encyclopedia Brittanica, telemetry is a "highly automated communications process by which measurements are made and other data collected at remote or inaccessible points and transmitted to receiving equipment for monitoring, display, and recording." Perhaps the highest profile user of telemetry is NASA, where telemetry has been used since 1965 to monitor the early Gemini missions to the modern Mars rover flights. At NASA's Mission Control Center, for example, dozens of specialists monitor telemetry data sent from sensors attached to a space vehicle and its occupants. This data is used for many purposes, including early warning of anomalies indicating problems, for better insight into the current status of the mission, and for the impact of making incremental course or mission adjustments.

We define "software project telemetry" as a style of software metrics definition, collection, and analysis with the following essential properties:

1. *Software project telemetry data is collected automatically by tools that unobtrusively monitor some form of state in the project development environment.* In other words, the software developers are working in a "remote or inaccessable location" from the perspective of metrics collection activities. This contrasts with software metrics data that requires human intervention or developer effort to collect, such as PSP/TSP metrics [8].

2. *Software project telemetry data consists of a stream of time-stamped events, where the timestamp is significant for analysis.* Software project telemetry data is thus focused on evolutionary processes in development. This contrasts, for example, with Cocomo [3], where the time at which the calibration data was collected about the project is not significant.

3. *Software project telemetry data is continuously and immediately available to both developers and managers.* Telemetry data is not hidden away in some obscure database guarded by the software quality improvement group. It is easily visible to all members of the project for interpretation.

4. *Software project telemetry exhibits graceful degradation.* While complete telemetry data provides the best support for project management, the analyses should not be brittle: they should still provide value even if complete sensor data is not available. For example, telemetry collection and analysis should provide decision-making value even if these activities start midway through a project.

5. *Software project telemetry is used for in-process monitoring, control, and short-term prediction.* Telemetry analyses provide representations of current project state and how it is changing at various time scales—we have so far found days, weeks, and months to be useful scales. The simultaneous display of multiple project state values and how they change over the same time periods allow opportunistic analyses—the emergent knowledge that one state variable appears to covary with another in the context of the current project.

Software Project Telemetry enables a more incremental, distributed, visible, and experiential approach to project decision-making. For example, if one finds that complexity telemetry values are increasing, *and* that defect density telemetry values are also increasing, then one could try corrective action (such as simplification of overly complex modules) and see if that results in a decrease in defect density telemetry values. One can also monitor other telemetry data to see if such simplification has unintended side-effects (such as performance degradation). Project management using telemetry thus involves cycles of hypothesis generation (Does module complexity correlate with defect density?), hypothesis testing (If I reduce module complexity, then will defect density decrease?), and impact analysis (Do the process changes required to reduce module complexity produce unintended side-effects?). Finally, Software Project Telemetry supports decentralized project management: since telemetry data is visible to all members of the project, it enables all members of the project–developers and managers–to engage in these management activities.

Software Project Telemetry is related to in-process software metrics, such as work done on management of software testing [9]. However, such work tends to focus on a narrow range of measures and management actions related to testing, and as a result can lead to manual collection and/or analysis of data. The broader scope of telemetry necessitates automated collection and analysis, with a corresponding broader range of management decision-making support.

Software Project Telemetry also relates in interesting ways to both the Capability Maturity Model Integration (CMMI) and Agile methods. The CMMI is a revision of the original Capability Maturity Model to incorporate lessons learned and to support more modern, iterative development processes. In an article on how to transition from CMM to CMMI, Walker Royce asserts the importance of "instrument[ing] the process for objective quality control. Lifecycle assessments of both the process and all intermediate products must be tightly integrated into the process, using well-defined measures derived directly from the evolving engineering artifacts and integrated into all activities and teams. [11]." Software Project Telemetry appears well suited to the CMMI vision for process improvement.

Agile method proponents are traditionally suspicious of conventional process and product measurements and technologies for project decision making. Jim Highsmith frames the problem as follows: "Agile approaches excel in volatile environments in which conformance to plans made months in advance is a poor measure of success. If agility is important, then one of the characteristics we should be measuring is that agility. Traditional measures of success emphasize conformance to predictions (plans). Agility emphasizes responsiveness to change. So there is a conflict because managers and executives say that they want flexibility, but then they still measure success based on conformance to plans. [7]." Software Project Telemetry provides an infrastructure for measurement that is not focused on whether a particular long-range target was achieved, but rather whether the process and product measurements indicate adaptation and improvement over the recent past.

3. Supporting Software Project Telemetry

For the past several years, we have been designing, implementing, and evaluating tools and techniques to support a telemetry-based approach to software project management as part of Project Hackystat. Figure 1 illustrates the overall architecture of the system. First, the project development environment must be instrumented by installing Hackystat sensors, which developers attach to the various tools such as their editor, build system, configuration management system, and so forth. Once installed, the Hackystat sensors unobtrusively monitor development activities and send process and product data to a centralized web service. Project members can log in to the web server to see

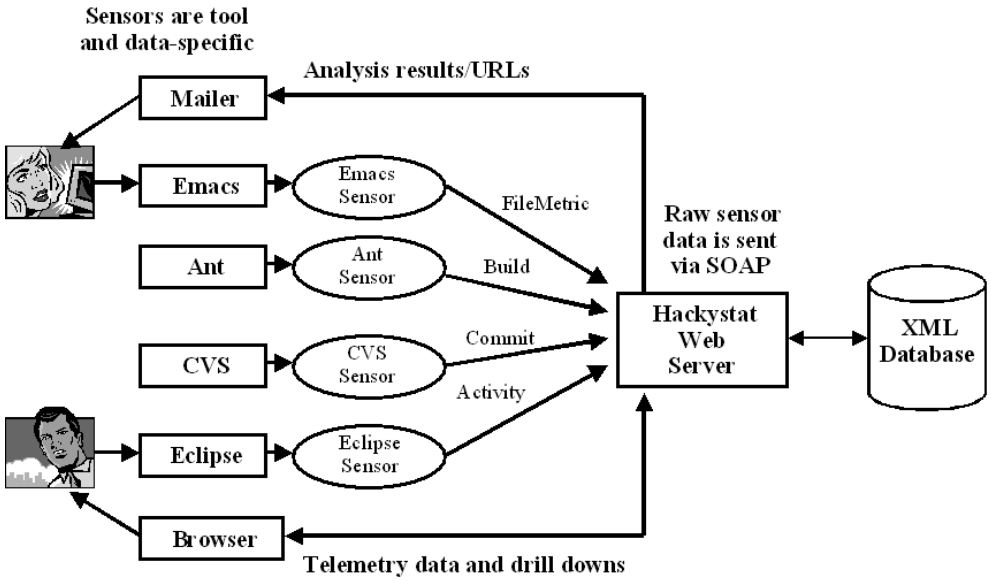

Figure 1. The basic architecture of Hackystat. Sensors are attached to tools directly invoked by developers (such as Eclipse or Emacs) as well as to tools implicitly manipulated by developers (such as CVS or an automated build process using Ant).

the collected raw data and run analyses that integrate and abstract the raw sensor data streams into telemetry. Hackystat also allows project members to configure "alerts" that watch for specific conditions in the telemetry stream and send email when these conditions occur.

Hackystat supports the following general classes of software project telemetry:

- *Development telemetry* is data gathered by observing the behavior of project developers and managers as reflected in their tool usage, and includes information about the files they edit, the time they spend using various tools, the changes they make to project artifacts, the sequences of tool or command invocations, and so forth. Development telemetry can be gathered by attaching sensors to editors, such as Eclipse or Emacs, to Office applications such as Word or Frontpage, to configuration management tools such as CVS, to issue management tools such as Bugzilla or Jira, and so forth.

- *Build telemetry* is data gathered by observing the results of tools invoked to compile, link, and test the system. Build telemetry can be gathered from build tools like Ant, Make, or CruiseControl, testing tools like JUnit, size and complexity tools like LOCC, and so forth.

- *Execution telemetry* is data gathered by observing the behavior of the system as it executes. This telemetry can be gathered by instrumenting the run-time environment of the system to collect data about its internal state (heap size, occurrence of exceptions, etc.) as well as by tools that perform load or stress testing of the system, such as JMeter.

- *Usage telemetry* is data gathered by observing the behavior of users as they interact with the system, such as the frequency, types, and sequences of command invocations during a given period of time in a given subsystem.

For a description of the specific sensors and data types currently supported by Hackystat, see Section 8, Sidebar.

The path from sensors to the telemetry report displayed in Figure 2 involves several steps. First, "raw"

sensor data is collected by observing behavior in various client systems and then sent to the Hackystat server, which it is persisted in an XML-based repository. The raw sensor data is abstracted into "DailyProjectData" instances, which can involve the synthesis of sensor data from multiple group members and/or multiple sensors into a higher level representation of sensor data for a given project and day. Sets of DailyProjectData instances are then manipulated by "Reduction Functions", which emit a sequence of numerical telemetry values for a given project and time scale of days, weeks, or months.

The previous steps occur "below the hood", as part of the software implementation of telemetry support. An important benefit of Hackystat is its explicit support for the exploratory nature of telemetry-based decision making. We have designed a "Telemetry Display Language" that can be used with the Hackystat web server to interactively define telemetry streams and specify how they should be composed together into charts and reports for presentation to developers and managers.

Figure 2 shows an example telemetry report. This report illustrates the relationship between aggregate code churn (the lines added and deleted from the CVS repository by all members of the project) and aggregate build results (the number of build attempts and failures on a given day via invocation of the Ant build tool). Note that Telemetry Reports are always defined without reference to a specific project or time interval. The specification of the project and time interval for presentation in the report is specified when the report is generated, not as part of its definition. Thus, project members can now run this telemetry report over differing sets of days, or else change the time scale to Weeks for Months to see if different trends emerge from these alternative perspectives. In addition, once defined, members of other projects on this server could use the BuildAndChurn telemetry report to see if it adds decision-making value to their project management activities.

4. Telemetry in practice: managing integration build failure

As a concrete example of software project telemetry in action, we are currently using it to investigate and improve our own daily (integration) build process. Hackystat consists of approximately 65 KLOC, organized into approximately 30 modules, with 5-10 active developers. The sources are stored in the CVS configuration management system, allowing developers to check out the latest version of the sources associated with any given module, and commit their changes when finished. Developers rarely compile, build, and test against the entire code base, instead selecting a subset of the modules relevent to their work. An automated nightly build process compiles, builds, and tests the latest committed code for all modules and sends email if the build fails. We can also invoke this integration build manually.

At the end of 2004, we discovered that our integration build failure rate was significant: for the 300 daily integration build attempts during that year, the build failed on 88 of those days with a total of 95 distinct build errors. The impact on our productivity of this high failure rate is substantial, since each integration build failure generally requires one or more members of the team to stop concurrent development, diagnose the problem, determine who is responsible for fixing it, and often wait until the corrections have been committed before checking out or committing additional code.

In order to reduce the rate of integration build failure in 2005, we needed to understand more about how, when, and why the builds were failing in 2004. To do this, we embarked on a series of analyses involving several Hackystat sensor data streams: Active Time, Commit, Build, and Churn. This revealed many useful insights about our build process. First, we could partition the 95 distinct build errors into six categories: Coding Style Error (14), Compilation Error (25), Unit Test Error (40), Build Script Error (8), Platform-related Error (3), and Unknown Error (5). Second, we found substantial differences between experienced and new developers with respect to integration build failures. For example, the least experienced developer had the highest rate of integration build failure: an average of one build failure per four hours of Active Time. In contrast, more experienced developers averaged one build failure per 20 to 40 hours of Active Time. Third, the two modules with the most dependencies to other modules also had the two highest numbers of build failures, and together accounted

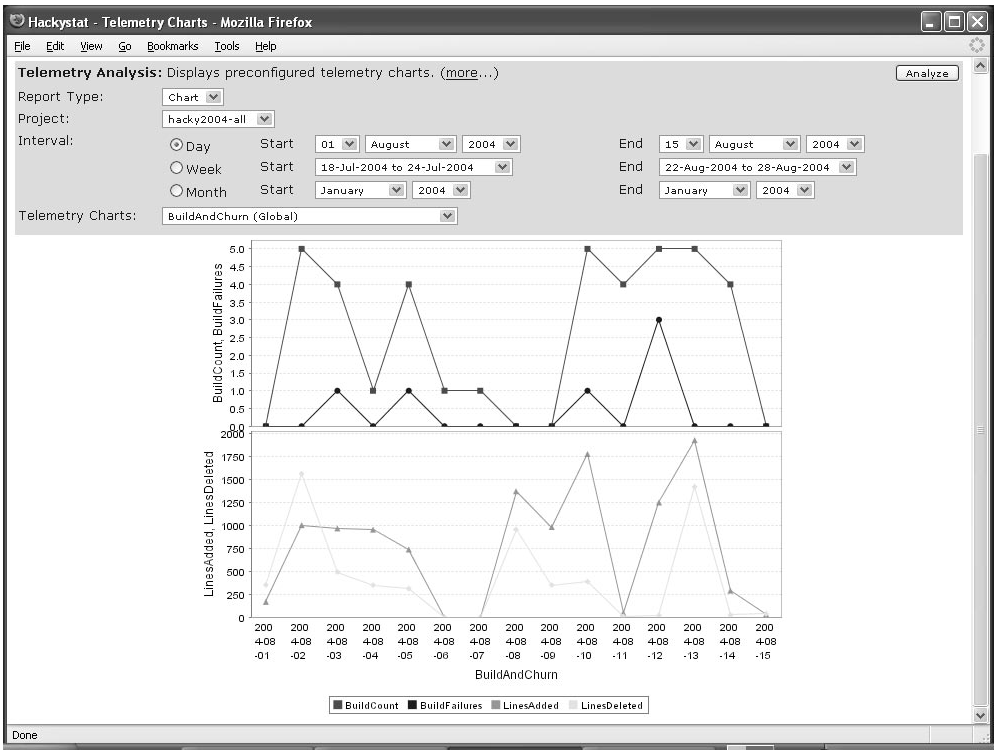

Figure 2. A telemetry report that compares code churn (lines added and lines deleted) to build results (number of build attempts and number of failures.

for almost 30% of the failures. Fourth, we found that the 88 days with build failures had, on average, a statistically significant greater number of distinct module commits than days without build failures. Fifth, we found (somewhat unexpectedly) that there was no relationship between build failure and the number of lines of code committed or the amount of Active Time spent before the commit. In other words, whether you worked five hours or five minutes before committing, and whether you changed 5 lines of code or 500 didn't measurably change the odds of causing a build failure.

These findings yield a number of hypotheses regarding ways to reducing integration build failure, including increased support for new developers such as pair programming, and refactoring of modules to reduce coupling and the frequency of multi-module commits. The most provocative hypothesis, however, is that 82% of the 2004 integration failures could have been prevented if the developers had run a full compile and test of the system before committing their changes.

The most simple, and most intrusive, process "improvement" would require all developers to run a full compile and test of the system locally before every commit. However, even though some commits without testing result in an integration build failure, many other commits without testing do not. Given that a full compile and test can take between 10-20 minutes depending upon the machine, and that multiple developers often perform multiple commits per day, the productivity cost of this process improvement could actually exceed the benefits from reducing the current level of integration build failures! Other "generic" changes, such as moving to continuous integration, also tend to move the costs of build failure around without necessarily reducing them.

Our current approach to managing integration build failure comes from recognizing that the decision about whether to invest the time to perform a full build and test before any particular commit is a complicated one, involving developer familiarity with the system, the actual changes made to the code, the commits being made concurrently by other developers, and so forth.

To improve our productivity, we need to give developers the tools and feedback necessary to better decide when a specific commit should be proceeded by a full build and test. To assess whether the feedback is working, we can use Software Project Telemetry.

Our analyses demonstrate that understanding the causes of success or failure of any given integration build requires multiple forms of process and product information, including the occurrence of local builds, the success or failure of the integration build, the type of failure, the modules that were committed, the developers responsible, the dependency relationships between modules, and the Active Time associated with the work prior to commits. Unfortunately, we have not discovered any analytical model that could automate the decision making process and tell a developer before they commit whether full or partial testing is needed. However, using Software Project Telemetry, we can track the absolute level of integration build failures over time, as well as the number due to any particular cause, and even the number that could have been prevented by a prior full build and test. Using Hackystat's alert mechanism, we can provide developers a detailed summary of the process and product state, including the factors we have identified as relevent, whenever an integration build failure occurs. Our hypothesis is that, given appropriate feedback, each developer will naturally learn over time to be more sophisticated in deciding when to perform a full build and test. New developers might quickly learn to do it almost all of the time, while more experienced developers might begin to recognize more complex indicators. One of our project goals for 2005 is to test this hypothesis, and measure the results using integration build failure telemetry streams.

5. The Telemetry Control Center

For a project of even moderate size and complexity, the number of possible telemetry charts and reports quickly explodes. For example, the Hackystat development project is monitored by almost a dozen different sensor data streams, across 30 modules, from 5-10 active developers. Given that each telemetry stream can be composed from one or more sensor data streams, one or more project modules, and one or more developers, you can see the problem: which of the literally thousands of possible charts should we be monitoring?

In our development group, we decided to address this problem by creating a new interface to the telemetry data that would enable us to passively monitor telemetry in a way that a standard web browser would not allow. We call this interface the "Telemetry Control Center", as shown in Figure 3.

The Telemetry Control Center consists of a standard PC with a multihead video display card that is attached to nine 17" LCD panels, mounted on the wall in our laboratory. We implemented a new client-side software system called the TelemetryViewer, which periodically requests Telemetry Reports from the Hackystat server, retrieves the resulting image file, and displays them on screens. The TelemetryViewer reads in an XML configuration file at startup, which tells it which reports to retrieve, where to display them, and how long to wait before retrieving the next set of reports. The default behavior of the TelemetryViewer is to automatically and repeatedly cycle through the set of telmetry "scenes" specified in the XML configuration file.

The Telemetry Control Center frees us from the "tyranny of the browser", by making a sequence of telemetry report sets continuously available without any action on the part of developers. It also enables us to more easily look for relationships between telemetry streams, since the system can display nine telemetry reports simultaneously. Finally, it provides a new kind of passive awareness about the state of the project to all developers; rather than having to decide to generate a report or wait for a weekly project update meeting, developers can simply glance at the Telemetry Control Center whenever they are passing though the lab to get a perspective on the state of development. Of course, individuals can still get all of the Telemetry Control Center reports on their local workstations if they so desire, although without the simultaneous display.

6. Lessons Learned

Our first lesson learned is that software project telemetry can provide useful support for project management decision making. In addition to our work on integration build failure, telemetry data has also re-

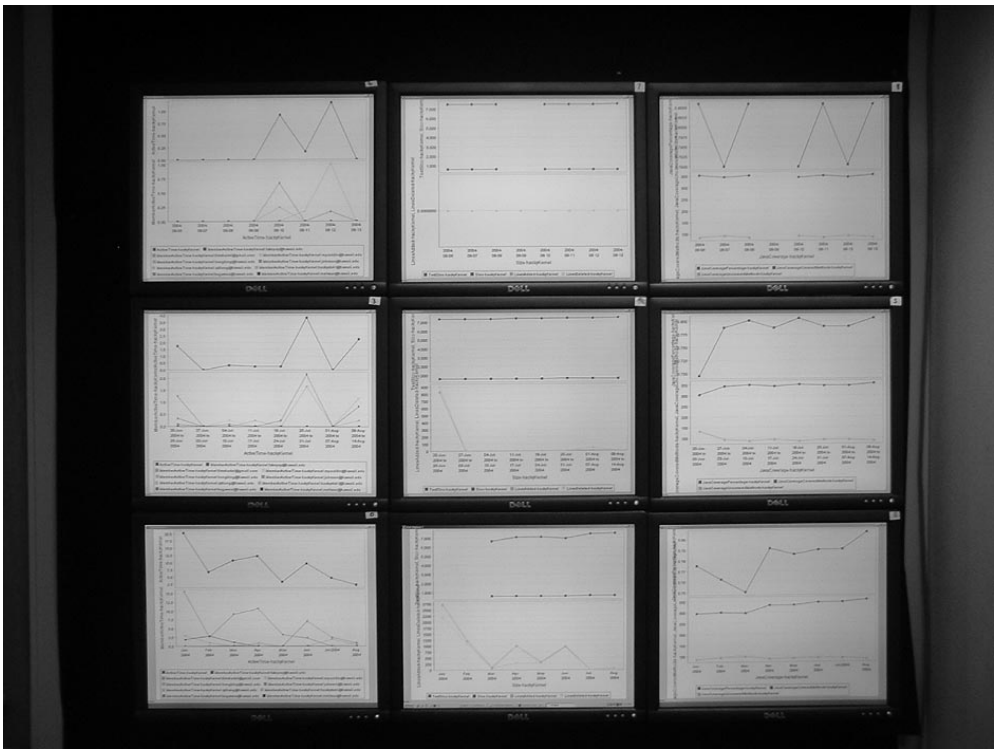

Figure 3. The Telemetry Control Center, showing one "scene" consisting of nine telemetry reports. The associated TelemetryViewer software controls the TCC by automatically cycling through a set of scenes at a predefined interval. This telemetry viewer is configured to show a dozen separate scenes, each displayed for two minutes.

vealed to us a recent, subtle slide in testing coverage over the past six months that has co-occurred with two episodes of significant refactoring (and resulting code churn). As a result, we are allocating additional effort to software review with a focus on assessing the test quality of new modules. We hope that this project management decision will lead to a reversal of the declining coverage trend.

Hackystat provides an open source reference framework for Software Project Telemetry, but Hackystat is not the only technology available. Commercial measurement tools can also provide infrastructure support, or your organization could decide to develop technology in-house. The key issue is to preserve the essential properties of software project telemetry.

We have learned that having an automated daily build mechanism adds significant value to software project telemetry. It both provides a convenient hook into which you can add sensors to reliably obtain daily information about product measures, but also provides a kind of heart beat for the development project that makes all the metrics more comparable, accessable, and current.

As with any measurement approach, social issues must be taken into account. It is possible to misinterpret and misuse software project telemetry data. For example, telemetry data is intrinsically incomplete with respect to measuring "effort". Hackystat implements a measure called Active Time, which is the time developers and managers spend editing files related to a given project in tools such as Eclipse, Word, or Excel. However, many legitimate and productive activities, including meetings, email, and hallway conversations are outside the scope of telemetry-based measurement. Telemetry cannot measure "effort" in its broadest sense, and a small value of Active Time by a project member does not necessarily imply that they are not contributing a great deal of productive effort

to the project. Indeed, some organizations may decide not to collect measures such as Active Time, simply because it is susceptible to misinterpretation and/or abuse. Robert Austin provides an excellent analysis of these and other forms of "measurement dysfunction" [1].

The adoption of a software project telemetry approach to measurement and decision making tends to exert a kind of gravitational force toward increased use of tools for managing process and products. For example, a small development team might begin by informally managing tasks and defects using email or index cards. As they start to adopt telemetry-based decision making, they will inevitably want to relate development process and product characteristics to open tasks, defect severity levels, and so forth, but not be able to do so unless they move to an issue management tool such as Bugzilla or Jira that enables sensor-based measurement.

7. Future directions

Does software project telemetry provide a silver bullet that solves all of the problems associated with metrics-based software project management and decision making? Of course not. While software project telemetry does address certain problems inherent in traditional measurement, and provide a new approach to more local, in-process decision-making, it provides its own set of issues that must be addressed by future research and practice.

First, the decision-making value of telemetry data is only as good as the quality and diversity of data that can be obtained by sensors. Clearly, there is some threshold for sensor data, beneath which the decision-making value of software project telemetry is compromised. But what is this threshold, and how does it vary with the kinds of decision-making required by the development group? What set of sensors and sensor data types are best suited to what project development contexts?

Second, what are the intrinsic limitations to telemetry-based data? A good way to investigate this question involves qualitative, ethnographic research, in which a researcher trained in these methods observes a software development group to learn what kinds of information relevant to project management decision-making occur outside of the realm of telemetry data.

Third, while manual investigation of telemetry streams and their relationship to each other is certainly an important and necessary first step, the sheer number of possible relationships and interactions means that only a small percentage of them can be inspected and monitored manually on an ongoing basis. An intriguing future direction is to explore the use of data mining and clustering algorithms to see if they can reveal relationships in the telemetry data that might not be discovered through manual exploration.

Fourth, what are the costs associated with initial setup of Software Project Telemetry using a system like Hackystat? Unfortunately, we cannot use Hackystat to measure the effort involved with installation of Hackystat. Furthermore, some organizations will require development of new sensors or analyses not available in the standard distribution. Better understanding of these costs will aid adoption of this technology and method.

8. Sidebar: Sensors and Sensor Data Types

Hackystat provides an extensible architecture with respect to both "sensors", or the software plugins associated with development tools, and "sensor data types", which describe the structure of a given type of raw metric data. This mapping is not one-to-one: for example, the Eclipse sensor can send Activity, FileMetric, and Review sensor data types, and the FileMetric sensor data type can be collected by both IDE and Size metric sensors. The following lists describe the range of currently available sensors and sensor data types; each organization can decide whether or not to enable these facilities, or whether to implement their own custom extensions to better facilitate their own needs.

Hackystat sensors are currently implemented for the following tools:

- *Interactive development environments*, including Eclipse, Emacs, JBuilder, Vim, and Visual Studio;
- *Office productivity applications*, including Excel, Word, Powerpoint, and Frontpage;

- *Build tools*, including Ant and the Unix command line;
- *Size measurement tools*, including CCCC and LOCC;
- *Testing tools*, including JUnit and JBlanket;
- *Configuration management*, including CVS and Harvest;
- *Defect tracking tools*, including Jira;

Hackystat sensor data types include:

- *Activity*, which represents data concerning the active time spent by developers in their IDE;
- *BufferTransitions*, which represents the sequence of files visited by developers;
- *Review*, which represents data on review issues generated during code or design inspections;
- *FileMetric*, which represents size information about files;
- *Build*, which represents data about the occurrence and outcome of software builds.
- *Perf*, which represents data about the occurrence and outcome of performance analysis activities such as load testing;
- *CLI*, which represents data about the occurrence of command line invocations;
- *UnitTest*, which represents data about the occurrence and outcome of unit test invocations;
- *Coverage*, which represents data about the coverage obtained by unit testing activities;
- *Commit*, which represents data about configuration management commit events by developers;
- *Defect*, which represents information about the posting of defect reports to defect tracking tools by developers or users

Hackystat is an open source system that is freely available for download and use. We encourage interested theorists and practitioners to visit the developer services website at http://www.hackystat.org, where access to source, binaries, and documentation is available. To try out Hackystat, we also maintain a public server at http://hackystat.ics.hawaii.edu.

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