PROGNOSTICS FOR BUS-ARCHITECTURE VEHICLES

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ABSTRACT

The goal of *condition-based maintenance* (CBM) is to optimize operational readiness of equipment through predictive and proactive maintenance. This capability requires accurate prediction of the remaining useful lifetime of each component, so that each may be replaced shortly before it is likely to impair mission readiness. By reducing unnecessary component replacements while still providing effective maintenance, effective Condition Based Maintenance ensures reliability of the warfighter's equipment at lessened expense, thus enhancing mission capability.

The practice of forming predictions of component reliability is called prognostics. In this paper we consider the application of prognostics to military vehicles utilizing data bus architecture, particularly in the context of the *Advanced Multiplex Test System* (AMTS). We discuss several methods of designing prognostics (including incorporating the use of machine learning) as well as the barriers existing in this domain environment both to design and implementation of effective predictive maintenance. We present a variety of suggestions for a gradual approach to developing prognostics capabilities in this setting.

1. INTRODUCTION TO PROGNOSTICS

The intent of condition-based maintenance (CBM) is to optimize operational readiness by intelligent replacement of components only shortly before they would become operation incapable. For this concept to be implemented in an economically sustainable way, it must be possible to predict with reasonable reliability the time to failure for each individual component, based on its actual operating environment, monitored health, and usage level. The study and practice of failure prediction for components is known as *prognostics*. Note how this is distinguished from *diagnostics*, which concerns only the analysis of the current condition and capability of components, and of the causes of existing failures.

In the context of this study we focus on field maintenance. Maintainers in our domain setting cannot attempt to repair a component themselves, only decide whether or not to replace it (and send it to the depot for bench service). This decision to retain or replace is based on guidelines known as *replacement rules*. This limitation somewhat simplifies the prognostics issues.

1.1. Possible indicators of useful lifetime remaining

There are three general classes of data that may be utilized in deriving an estimate of remaining useful life of a component.

The simplest type of data to capture, and historically, that first used for prognostics is given by:

Elapsed time. This is sometimes defined as the time that the unit has been in active use, and sometimes as total time elapsed (which may be measured either from the date of a component's manufacture, or from its last bench service).

The assumption that the probability of failure is a simple function of time leads to easy replacement rules. However, often failure probability is not a simple function of time. In a landmark study of aircraft components, six categories of age-reliability curves were observed. Of these six, only three reflected failure patterns that might benefit from imposing a limit on operating age; and these three types were observed in only 11% of all components studied (Nolan and Heap, 1978).

The demonstrated inadequacy of solely time-based predictions leads to:

Current measured condition. Here, replacement guidelines are based on measurable or observable aspects of the component's current condition. Typically this might be defined as deviation of one or more health or performance metrics from certain pre-defined acceptable ranges for that type of component.

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This concept is simple and the principle seems obvious. However, even here, there are pre-suppositions that do not hold for all types of components and types of failures. It must be possible to detect some condition indicating potential future failure, and there must some reasonable consistency in the period between this condition manifestation and failure of the item. Implementation even then may be difficult. New sensors may be required for monitoring conditions continuously. In some cases, the use of sensors or monitoring equipment may be incompatible with normal operating conditions. If maintenance inspections require a special working state, certain problems may not manifest in this state. The root assumption itself, that future behavior may be inferred from current performance, is not true in all cases.

Trends (changing behavior patterns). This approach involves detecting a pattern of increasing deviation over time of one or more metrics from recorded historical ranges for that particular component, or for that that type of component. A sudden shift in the rate of change is a likely indicator of increased loss of reliability.

As this approach combines the two above, it is the most complex to design and implement. Again, it is necessary to determine a characteristic that can be tracked and for which some change in behavior is reasonably correlated with eventual failure, although this correlation need not be so tightly time-based as in the second approach.

1.2. Determinations necessary for the formation of prognostics replacement rules

Note that any attempt to design meaningful replacement strategies requires deep and substantial knowledge of component performance. A sample of the types of questions which need to be addressed:

- What class of function best approximates the time- or condition-based expectation of failure? How can one derive parameters for this function?
- Which specific measurements or phenomena are most associated with decaying performance? How can one determine acceptable ranges?
- Precisely which physical measures are important to track over time? What constitutes performance variation which is not merely unusual, but unsafe?
- Do performance parameters vary based on operating environment?

In the setting of this study, a system component that has been removed from a vehicle in order to receive bench service may afterwards be installed in another vehicle elsewhere.

- Is it possible for a single reliability model to function effectively regardless of usage, or do environmental factors require consideration and adjustment?
- If a component has been previously used in a different system, how comparable is the old usage to the new? Should this be taken into account when formulating a prediction, and if so, how?

1.3. Some general strategies for determining and assessing prognostics factors

Data collection and analysis. Such a process often begins with lab data gathered under controlled circumstances, but ultimately requires field data for validation. Arrays of sensors and diagnostic equipment may be employed to gather exhaustive performance data. Gathered data, whether from the lab or field, is analyzed for specific indicators and patterns of performance degradation.

Expert systems. In cases where substantial direct data collection is impractical, it may be necessary to consult human experts with substantial experience observing and servicing the system. From their recommendations some “consensus advice” is derived. An expert system is a program that evaluates data and makes decisions based on these human recommendations.

Machine learning. Given some ability to ability to assess the consequences of a decision, machine learning can be utilized. This type of program makes recommendations based on every previous decision made and outcome recorded. Its behavior adjusts automatically; over time, its recommendations should become more accurate. Although such systems can eventually overcome incorrect initial models, they do require some amount of initial data in order to be able to offer non-trivial advice.

It is possible to create a system synthesizing elements from multiple design approaches as well.

There are some very accessible texts describing existing practices in predictive and preventative maintenance. In addition to Nowlan and Heap, 1978, another good general source is Leemis, 1995. So far as the authors are aware, the idea of applying artificial intelligence techniques to predictive maintenance is quite new.

1.4. Pragmatic limitations on determining and implementing replacement rules

Clearly, each of the above strategies may involve a certain amount of time, expense, and specialized resources, or may be infeasible in a specific domain for some reason. Obtaining trial data or expert advice may both be very difficult in some domains.

Even if replacement rules are somehow formulated, effective implementation requires careful record-keeping and the willing cooperation of maintainers.

Finally but importantly, in any given application it is difficult to estimate whether the cost of necessary equipment, software, and personnel hours to design and implement a maintenance plan incorporating prognostics may not, in practice, exceed the expected savings in unnecessary component replacement. Most of the cost is up-front, the savings to be realized in the future. However, historically, predictive maintenance plans have often paid for themselves many times over. For a number of striking case studies, see Kececioglu, 1995, pp. 8–17.

2. BUS-ARCHITECTURE VEHICLES: CONDITIONS AND POTENTIALS

The computer systems of certain military vehicles consist of separate digital components (*line replaceable units*, or LRUs) linked via a common data bus. The Army Communications and Electronics Command (CECOM) has developed a portable maintenance device which uses the bus mechanism to inspect all of these components, and to isolate any failures, in a single session. Information is presented to the user in a comprehensible way, obviating the need to refer to manuals. This device is the Advanced Multiplex Test System (AMTS).

AMTS is an excellent diagnostics tool. It is CECOM's intention to supplement its current capabilities by incorporating prognostic information and removal recommendations.

2.1. Prevailing conditions of the domain setting and avenues for reliability model development

Earlier we listed three general approaches to designing prognostication rules: data collection and analysis; expert systems; and machine learning. We also listed three general classes of data that may be utilized by replacement rules: elapsed time; current condition measurements; and trends. We mentioned some caveats, including variable usage conditions.

When we began this study, we therefore attempted to analyze the existing domain conditions affecting the various approaches to developing and implementing suitable replacement rules for the Line Replaceable Units (LRUs) on the data bus.

Some of the following information was obtained from discussions with CECOM personnel associated with the AMTS project. We also interviewed Army vehicle maintainers at the Johnstown PA aviation facility to gain further knowledge of domain specifics. Due to the time restrictions of our study and the difficulties of arranging civilian access to military facilities, we were unable to do a more complete analysis of the domain environment. We apologize if there are inaccuracies.

An obvious source for reliability data for a given electronic component is the manufacturer. However, the only reliability data readily offered by the manufacturers for the components in this study was the Mean Time Before Failure (MTBF). This information alone sustains only primitive elapsed-time replacement rules, the least effective type. An individual component costs thousands of dollars, so substantive lab testing with deliberately induced failures was fiscally impossible under our own study's operating conditions.

We had hoped to locate experts in systems maintenance for the various LRUs. The technicians to whom we spoke have only "black box" understanding of the individual components on the bus, since their only decision concerning a given LRU during a service session is whether or not to remove it from the vehicle. When a decision is unclear, they seek guidance from their superior officer—the closest approximation to a LRU expert with whom they have contact. The interior of an LRU is usually considered proprietary information of the manufacturer and Army personnel are not permitted to open the casing or to view a wiring diagram.

Once removed from a vehicle, an LRU is sent to the depot for repair. In most cases, this means it is sent to the manufacturer. So again, for most components, the only people with "expert" knowledge of an LRU are directly employed by the manufacturer. Such manufacturers have no economic incentive to reduce unnecessary bench services, which increase their own profits.

No indication is ever sent back to the service unit from the depot concerning the actual condition of an LRU that has been removed, e.g., whether it was indeed impaired in any way. The depot does file a discrepancy report, but the service unit has no access to this report; it is sent to the appropriate subordinate command of Army Materiel Command. Thus, a maintainer never learns whether the decision to remove an LRU was justified.

There is consequently no feedback which could be used in machine learning.

Vehicles using this particular bus architecture are in service in a wide variety of settings world-wide. Thus there can be considerable variation in the exposure to heat, humidity, dust, and so forth. Of course, vehicles can themselves move from one location to anther. Maintainers confirmed that climate (especially humidity) plays a definite role in certain types of failure of the LRUs on the bus, so such data would need to be reflected in reliability models.

An important aspect of this setting that by definition, a LRU may be removed from one vehicle and later installed on another vehicle, possibly in a distinct environment. Replacement rules relying on elapsed time (including trend-based rules) require that it be possible for the maintainers of a latter vehicle to obtain the service history of each transferred component. (The simplest of all replacement rules require knowing the age of the component.)

Under the current conditions, tracking of individual LRUs is imperfect. In interviews with technicians, we were told that most LRUs are tracked by serial number. There is no global electronic tracking agency for individual LRUs. Maintainers also admitted that not all LRUs are identified and tracked via serial number. The radio frequency identification tag (RFID) technology could be an eventual answer to accurate tracking, but such a system is not yet in place for LRUs.

Maintainer said that they have access to the entire service record for each LRU, including the date of manufacture, number of hours of service the unit had already clocked at time of its most recent installation, and installation date on the current vehicle. Service records, both in paper form and electronically, are filed for every service session for a vehicle. The paper records are described as very accurate.

Existence of electronic records would appear to imply the existence of a database of maintenance data that may be mined for performance parameters. When we attempted to pursue this avenue, we were advised not to proceed. Although the electronic report for an LRU failure includes a failure code, the code is not very specific. Moreover, apparently the data entry interface for this electronic report system is (or has previously been) by line entry—it is impossible to “back up” and correct a line previously entered. Since most of the users are inexperienced at data entry and consider their primary responsibility to be repair of the vehicle, not filing the electronic report, many entries in the database are suspect.

Attempting to analyze data in paper maintenance reports would require initial funds, personnel, and hours for data entry before any data analysis could begin.

Maintainers confirmed that an important source of information about impaired performance comes as verbal reports from the vehicle user. This is particularly critical in cases of *intermittent discrepancies*—problems observed only when the vehicle is in use, and not measurable under maintenance conditions (during which the vehicle is stationary).

It should be noted that under current regulations, no data recording device may be attached to the vehicle bus during missions. So unless these restrictions should be modified, any effective software interface for prognostics (or even diagnostics) must support maintainer entry of some data. Information about the location/climate could be entered by the user as well. (The vehicles in the study had a GPS unit, but it was not resident on the same bus.)

2.2. The Advanced Multiplex Test System (AMTS)

We now considered the suitability of utilizing the Advanced Multiplex Test System (AMTS) itself as a data gathering device (whether for reliability model development or for implementing replacement rules).

Since maintainers are already required to submit both paper and electronic reports for all maintenance performed, we knew that they would react poorly to AMTS if it increased their work burden instead of lightening it. It seemed ideal if AMTS could make automatic session records with very little effort on the part of the maintainer. For this to be possible, the AMTS should be able to capture identification information for the vehicles and LRUs. Since currently LRUs (and vehicles) do not have identification markings that can be captured electronically, identification codes would have to be entered manually. However, once entered, a record of these codes (for each individual vehicle) could be retained for use in all future sessions.

To give a rough summary of the AMTS bus-based diagnostic design: AMTS works by capturing very brief time samples of bus messages, while the vehicle is at rest. Some of its tests analyze the *data* passed within the content of messages, and others the actual *sequences* of the messages themselves. (For example, one message may solicit a response from some particular LRU; if the correct response is not sent, this indicates a possible problem.)

In addition, the AMTS makes use of readings from sensor-based diagnostic equipment. Currently such reading must be entered manually; however, the AMTS architecture is designed for extensibility in the anticipation that it be will eventually need to be capable of accepting sensor readings directly through I/O.

Finally, the AMTS also prompts for maintainer input of observations that may not be subject to direct reading, such as visual appearance of LRUs, and problems reported by vehicle users.

AMTS reports its summary as a complete picture of the current bus system state. In cases where there appears to be a problem, e.g. some LRU is not responding correctly, the maintainer can use the AMTS to investigate more thoroughly. The maintainer can make physical adjustments, followed by more bus message sampling, in order to isolate and eliminate failures. (For example, there may be a problem with cable connections rather than the LRU itself.) AMTS users report that they appreciate the way that this tool presents a complete system view. They appreciate the way it supports and enhances their own abilities for critical analysis of a problem, instead of being required to follow step-by-step text instructions founded on the presupposition of the single most likely single-point-of-failure—a supposition which may be inconsistent with the actual system state.

The AMTS includes a substantial database to enable it to analyze bus messages, and it can determine the organization of LRU types resident on a given vehicle bus. However, it currently lacks any ability to associate an identifier to a particular vehicle or to an individual LRU. Nor has it any ability to retain any data read from the bus (other than the most recent sample of bus messages), or data entered by the user. Thus, currently it has no capability to collect and store historical data as used in prognostics. It also currently has no innate ability allowing it to interact with other files, programs, or processes, such as an internet.

CECOM has not yet planned or budgeted for any mechanism for data collection from individual units, or for establishing a central database.

2.3. Summary of current domain conditions

- LRU manufacturers probably possess reliability data in excess of what they have made available to the Army.
- LRU manufacturers also employ the most knowledgeable experts in LRU service and repair, and indeed, most manufacturers enforce strict containment of that knowledge.
- There is at least one Army electronic database of LRU removal information, but the data is somewhat vague, there may significant corrupted entries, and entries are unassociated with any feedback about whether removal was justified.
- Independent lab testing would be expensive (due to high cost of LRUs) as well as time-consuming.
- The Army personnel making preventative LRU removals never receive any feedback on the correctness or timeliness of their choices.
- Most LRU depot maintenance is performed by manufacturers, who have no financial incentive to provide feedback on unnecessary LRU removal.
- Currently, there is neither global nor electronic tracking of individual LRUs. Tracking, when it occurs, is done via paper and (usually) serial number.
- Reliability models for vehicle LRUs would almost certainly need to reflect the location of vehicle use or its climate conditions. This information can change.
- Currently, AMTS cannot retain data or share it with other processes. It therefore lacks support capabilities for enforcing time-dependent replacement rules, or for gathering data for failure analysis or for machine learning.
- Certain indicators of impaired performance only occur when the vehicle is in use. Currently, such indicators are only observed and reported by humans.

3. AN ABSENCE OF EXPERTS

One unfortunate aspect of the current field maintenance situation is that the maintainers do not have knowledge of or access to more experienced experts (except other workers at their own sites). It seems quite likely that under current conditions, there are probably technicians with more maintenance experience overall, but there are no real known Army “experts” for any specified LRU. This also meant that we did not have an obvious way to solicit expert advice, such as could guide the choice of metrics and parameters for LRU replacement guidelines.

As a very simple first approximation to an expert system for prognostics, we suggest a secure internet-based service where maintainers could interact with one another online and seek removal recommendations for the various LRUs. Such a service would be more valuable if it incorporated a mechanism for the user to rate the usefulness of a given piece of advice, and stored these user responses (preferably displaying their statistical distribution). We observe that as optimal guidelines may reflect local conditions, it may be most effective if posts are associated with some location information. (The quality of advice would probably be much better if depot-level maintainers were involved.) Not only would maintainers' resources be widened, the advice and responses culled from such a site could form the nucleus data of an expert system.

As far as we can discern, there are currently no "experts" for a given LRU, other than depot technicians. However, it may be possible to "create" Army experts.

Since there are over a dozen LRUs resident on vehicle bus (and potentially as many as 31), it is unlikely that a field maintainer will develop an interest in the reliability behavior of a given type of LRU spontaneously. We suggest that a set of maintainers each be assigned a small number of specific LRUs, for which they should be designated as a "go to" person at their own site. The maintainers should be encouraged to make more detailed examinations and records of those specified LRUs during maintenance sessions, and attempt to deduce patterns. These maintainers should also be encouraged to participate in the online community proposed above. By making the responsibility for a given LRU focused, rather than distributed over a large number of LRU types, we believe that expertise specific to individual LRUs could be developed.

4. PROGNOSTICS DEVELOPMENT RECCOMENDATIONS

In attempting to design an approach to prognostics for the AMTS projects, several categories of issues must be considered.

4.1. Physical architecture

Physical architecture concerns the physical factors of a domain setting. The physical architecture for the AMTS project includes which vehicle models (and variants) are to be maintained by AMTS units; which LRUs are used on a specific vehicle, and their physical layout on its bus; the distribution world-wide of the vehicles being serviced; the existence and locations of LRUs which have previously been in service and are expected to be returned to service in the future (pending repairs); and the physical movements of vehicles and LRUs between locations.

Without an ability to associate an entire service history to an individual LRU, any judgment as to whether it should be replaced can only be based on current observable features, i.e., its current measurable state (no time-based features or trends). Currently, service histories are not available to the maintainer in electronic form.

Some recommendations based on physical architecture aspects:

- Design, budget, and develop a central database for tracking individual LRUs globally, with an expandable capacity for retaining histories, using a standard format such as XML and registered DoD namespaces. This database should be accessible by both field and depot level maintainers.
- Standardize the tracking identification of all LRUs, at least those having replacement values exceeding some set threshold.
- Radio frequency identification tag (RFID) technology may offer a practical tracking solution. This possibility should be investigated.

4.2. Information architecture

Information architecture consists of how data is measured, where the data is stored, and how various types of data can enter the system. Currently for AMTS, data enters through the bus and user entry only, with planned expansion to incorporate direct input from other diagnostic equipment. However, no data from a service session or specific to a vehicle is retained.

Some recommendations based on information architecture aspects:

- Contact the LRU manufacturers for any reliability information that they may be willing to share beyond what they currently provide.
- Initiate a maintainer's web forum, as discussed in the previous section.
- Likewise, recruit or designate Army maintainers to monitor and study specific LRUs in the course of their duties.
- Provide any known reliability information (and expert advice, where and as it becomes available) graphically to the maintainer, preferably via a (secure) web-based service.
- Expand the user interface capability of the AMTS unit to support entry of ID data for a given vehicle and its (key) LRUs. A copy of this data (say on a memory peripheral) should be stored with the vehicle (until electronic global tracking is fully operational), making such data entry a one-time necessity. Use a standardized format such as XML and appropriate registered DoD namespaces.
- Add to the AMTS an ability to load and update data from a removable memory peripheral, and

eventually from a remote source via network or secure internet (such as NIPRNET).

- Add to the AMTS an ability to save key characteristics of session data, starting with basics such as date of service, location, and any LRU replacements. Use a standardized format such as XML and appropriate DoD namespaces (developing and registering new ones if necessary). Assume that data fields may change over time.
- To eliminate the necessity of duplicate data entry by maintainers, provide a mechanism for conversion of the session summary data as described above into any required report formats (electronic or human-readable).
- Begin database design for maintenance records, and determine data collection mechanism. Secure network access with asynchronous update seems most practical and effective.
- The database should also be designed to accept depot maintenance feedback for a given LRU. This data would allow machine learning to be incorporated into prognostication software, permitting gradual automated improvement of replacement recommendations.

4.3. Organizational architecture

The organizational architecture describes the intended use and deployment of a system. It includes what types of users the system will have, and how these various types of users will interact with the system. In a military context it also includes the Army organizational structure and its policies. For AMTS, we consider both field and depot maintainers, and also Army practices affecting them.

To some small extent, one of the proposals above does cross into organizational issues. By establishing a net-centric community in which maintainers at different locations and levels of expertise can interact, an alternative information mechanism becomes available, one outside of Army organizational lines.

As we have outlined, most LRU manufacturers provide little reliability information, and also are the sole source of depot maintenance for their products. They do not provide feedback to the field maintainer on inappropriate LRU removals, nor is it in their fiscal interest to do so.

Although the Army Aviation Condition Based Maintenance Plus (CBM+) Plan (Enderle, 2004) describes the necessity of a close working relationship between manufacturer and Army engineers in developing effective algorithms and metrics for maintenance, it does not explain how this cooperative state is to be brought about. The plan does not address the lack of feedback for preventative LRU removals.

Realistically, there is little CECOM can do directly that can change organizational issues, which hinge on Army policies. Thus, our only recommendations based on organizational architecture issues are really addressed to Army practices:

- Advocate change in Army policies regarding purchase and service contracts. Reasonably substantial and informative reliability information should become a pre-condition to purchase of new units. Service contracts with outside providers should include a proviso that field maintainers will receive some meaningful and reasonably timely feedback about the condition of LRUs they removed. Preferably, such feedback will eventually occur concurrent or en route to an update of the proposed maintenance database, so that this feedback information becomes part of the permanent record (and can be incorporated into machine learning).
- For manufacturers wishing to retain tight proprietary control of service and of performance data, an option is for the Army to require the manufacturers themselves to provide clear, enforceable reliability replacement rules. Service terms should be designed to reduce the financial incentive of unnecessary removals. For example, for LRUs removed under these preventative rules, service fees might be based on net vehicle mission hours, rather than per unit processed.

CONCLUSIONS

An effective system for preventive and predictive maintenance can result in savings many times in excess of its initial and support costs. Such an approach is particularly vital in times of flat military budgets and the necessity of maintaining legacy and often technically obsolete equipment. Operational lifetimes of U.S. military vehicles are currently being extended significantly beyond the original design limits. In the 1990s the Air Force observed the mission capability of its fleet declined 10%, largely due to the age of the avionics; by 2001, it was spending over $250 million a year coping with obsolescence issues (CETS, 2001). As maintenance costs increase, they consume a greater share of the military budget. More and more, the Army is realizing that equipment acquisition must be assessed in terms of total cost of ownership.

In this study, we focus on field maintainers using the Advanced Multiplex Test System (AMTS) diagnostic tool. Existing domain circumstances make development and implementation of effective predictive maintenance for vehicle Line Replicable Units (LRUs) very difficult. However, we have outlined a few initial steps that could provide some immediate assistance to the field maintainer in making replacement decisions, while enabling collection of data that could support an eventual global net-centric, self-evolving capability for prognostics.

We propose a data-collection mechanism which would actually lighten maintainers' recordkeeping. We also describe a simple means for culling human advice and for creating "experts," as well as a means of making their advice readily available to other maintainers. These precursor steps can gather seed data for mining (to determine patterns of failure), and gradually enabling more rigorous future collection of data suitable for model validation (to verify or adjust inferred patterns), and machine learning (to allow continuous refinement of failure models and deeper incorporation of operational environment). As unique identification, embedded diagnostics and health utilization monitoring systems become available, AMTS will be ready for true condition-based maintenance.

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