# The Blackboard: A Strategy for Laboratory Robotics

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Efficiency and flexibility are frequently in conflict in laboratory robotics. Furthermore, a complicated robotic procedure is usually costly to develop and difficult to make reliable. In this paper we will describe a dynamic robotic control strategy that enables more flexible robotic control with only a reasonable sacrifice of efficiency.

## INTRODUCTION

The most fundamental strategy for laboratory robot control is to build a set of simple unit operations from a collection of defined positions and movements. Analysis and sample preparation procedures using the robot then become sequences of these unit operations. In this paper we will describe the blackboard paradigm combined with robotics as a comprehensive strategy for designing and implementing flexible robotic procedures under expert system control.[1]

In laboratory robotics, efficiency and flexibility are frequently in conflict. Because a complicated robotic procedure is usually costly to develop and difficult to make reliable, laboratory robots are normally applied to tasks that are simple and repetitive.[2] In this work we will describe a dynamic robotic control strategy that enables more flexible robotic control.

Most analytical procedures can be divided into sampling, measurement, and interpretation. The traditional robotic control goes through every analytical step in a fixed sequence. This fixed sequence does not allow flexible robotic procedures. In an attempt to develop flexible procedures, a "blackboard" control strategy is described. Designed to reflect the fundamental steps of the automated chemical analysis process, this system includes four separate knowledge sources; one each for sampling, measurement, interpretation, and robot control. Note that in this paper we use the term "knowledge source" to describe a collection of general information or expertise. In contrast, we use the term "database" to refer to raw, usually numerical, data. These knowledge sources communicate with each other only through the blackboard, which is a place to store all the incoming information as global data. Conclusions drawn from any knowledge source may be used to modify the information on the blackboard. The general strategy of the system is as follows:

1. Define a subgoal.
2. Generate alternate procedures.
3. Establish priority of procedures.
4. Retrieve required unit operations from knowledge bases and place on the blackboard.
5. Assemble highest priority procedure possible from blackboard information.
6. Execute the procedure.
7. Repeat from step 1 above until all subgoals that make up the problem are achieved.
8. Interpret and report results.

Because this is a goal-driven strategy that requires a search for the best solution rather than a fixed procedure, the optimized examination of all possible strategies to accomplish a goal is assured. As all completed goals share results through the blackboard, subsequent goal seeking is done with the knowledge of previous results. This goal-seeking strategy provides a flexible environment for laboratory robotics. A chemical analysis example will be used to demonstrate the approach.

## ANALYTICAL DIRECTOR[3]

This project is part of a larger on-going project; the development of a system which we call "The Analytical Director". The fully implemented "Analytical Director" will be able to design, test, modify, and implement its own analytical procedures. The final goal of this project is to construct a computer-controlled robotic system and to make this system act like an expert analytical chemist.

## OVERVIEW

Since the introduction of the laboratory robot in the early 1980s, many people expected these one-hand all-purpose robot systems would eventually be able to perform all analytical tasks efficiently and flexibly. Initially, applications of laboratory robotics spread quickly to industrial and research laboratories. However, recently, users seem to be depending more on dedicated automation. Some reasons for this are[3-5]

1. Simple procedures are frequently very difficult to adapt for robots.
2. Application programming is very difficult and time consuming.
3. Robot procedures, once completed and optimized, are difficult to modify.
4. The level of technician support required by a robotics laboratory is much higher than first expected.

All these difficulties have tended to limit robotic applications to simple QC/QA tasks that implement invariant steps for sample preparation.

To overcome some of these restrictions, a flexible and user-friendly development and control strategy must be used. Generally, the hardware configuration of the robot is fixed, but the analytical sequences used should be easy to change for different sample conditions and different analytical methods. To program a complete robotic application is both time-consuming and difficult to make reliable. For example, titration procedures can take several hours to program and another half-hour to execute when using a general purpose robot.[6] By using an automatic titrater, a device optimized for this specific purpose, the same process can be finished within minutes. To address this problem, the robot control system should be able to manage and evaluate new analytical procedures using appropriate parts of tested procedures. This can be accomplished by using the blackboard strategy to assemble new procedures. The blackboard system is used to increase

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a ATTGP.SUB

```
rem attach general purpose hand
clear.gp.hand
hand1pos1
hand1pos2a
hand1pos3
clear.gp.hand
```

PARKGP.SUB

```
rem park general purpose hand
clear.gp.hand
hand1pos3
hand1pos2p
hand1pos1
clear.gp.hand
```

b WEIGH.SUB

```
attgp.sub
opendoor.sub
gettube.sub
tare
puttubebal.sub
closedoor.sub
gettubebal.sub
puttube.sub
parkgp.sub
print weigh
```

c SAMPLE PREPARATION PROCEDURES

```
Method?
1) basic titration
2) spectrophotometric titration

Sample State?
1) solid
2) liquid

Amount?
1) suitable for analysis
2) need to modify

Robotic procedures after query process

Weigh.sub
Dilute.sub
```

**Figure 1.** (a) Two fundamental robotic procedures. (b) Basic robotic unit operation. (c) Analytical procedure for sample preparation.

the flexibility of robot control and procedure design. The time spent on each robotic movement will still depend on the robot used and the efficiency of the primitive robot routines.

## ROBOT CONTROL

Normally, the development of a laboratory robot control procedure involves four steps.

1. Define positions.
2. Define movements from the positions.
3. Define unit operations from movements.
4. Define procedures from unit operations.

Usually, simple robotic procedures can be set up using traditional robot control strategies. In our laboratory, a Zymate II robotic system (Zymark Corp., Hopkinton, MA) was used. The robot positions, movements, unit operations, and analytical procedures could be defined using the Zymate robot controller. A series of basic robotic positions could be defined and named such things as HAND1POS1, HAND1POS2A, HAND1POS3, and CLEAR.GP.HAND according to their usage. These positions could be sequenced to produce the wanted robot movements. For example, the routine ATTGP.SUB (attach the general purpose hand) consists of a list of positions, HAND1POS1, HAND1POS2A, HAND1POS3, and CLEAR.GP.HAND. This and similar sequences could be assembled to build the unit operations that are required to form complete robot procedures. Figure 1a shows two primitive robot operations, ATTGP.SUB and PARKGP.SUB. Figure 1b details a unit operation, WEIGH.SUB, that uses both of these. Figure 1c illustrates how to implement a robotic process for sample preparation using a simple dialogue with the user to gain information about the sample.

The application in Figure 1c is also a good example of traditional robot control. The control flow of this application relies on the usual fixed programming strategy. In the following we will describe a dynamic control strategy that takes advantage of the blackboard strategy.

## BLACKBOARD SYSTEM

The blackboard system can be described as a dynamic problem-solving environment. To illustrate the blackboard system, it is helpful to consider the general fundamentals of problem solving. The problem-solving skill of an expert depends primarily on two things, practical domain knowledge and reasoning skills.

Domain knowledge can be used to construct alternate solutions for each part of the problem. Each of these solutions can be treated as a fact related to the problem. A solution to the problem can then be sought by backward or forward reasoning using these facts.[7] This searching process guarantees a solution for the problem, if a solution exists. However, this exhaustive searching process could be extremely time-consuming. To minimize the search time, heuristic searching must be used. Heuristic searching is simply a searching strategy that constrains the search to knowledge that has a high probability of being useful. To implement an effective heuristic search, the domain knowledge needs to be organized carefully. In this work, the domain knowledge was stored in "if-then rule" format knowledge bases. To further increase the efficiency of the search, opportunistic reasoning can be used. Opportunistic reasoning is when pieces of knowledge are applied at the most opportune time.[8]

Frequently, the procedures used in robot applications share similar strategies. The usual analysis sequence can be divided into sampling, sample preparation, measuring, and data processing.[9] This recurring theme allows the blackboard system to make use of a general control strategy for robotics in chemical analysis.

**Table I.** Blackboard System Knowledge Source

| knowledge source | related unit operations |
|---|---|
| sampling | weighing, dispensing, dilution, liquid/liquid extraction |
| measuring | titration, spectrophotometric measurement |
| interpretation | data interpreter, data processing function |
| robotic movement | all unit operations |

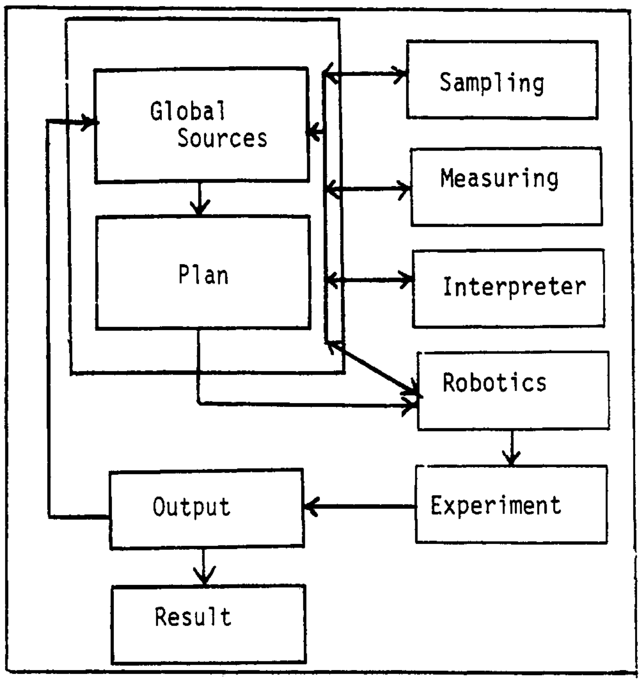


**Figure 2.** Diagram of a blackboard control system.

The flexibility of the blackboard comes from its control and management capabilities. To explain more about the blackboard system, two fundamentals of the system are emphasized below:

**(1) Blackboard Knowledge Sources.** The system contains knowledge sources for sampling, measuring, interpretation, and robot movement. Each knowledge source covers several basic operation procedures. Table I lists the content of these knowledge sources.

The blackboard control system accesses and extracts needed facts from these knowledge sources. To ensure that extracted information can be applied to related robotic procedures, every unit operation in the sampling and measuring knowledge sources must have a matching entry in the robot movement knowledge source. These robotic procedures can be activated by requests by the blackboard system. New procedures must update all relevant libraries to ensure that appropriate support information can be found.

**(2) Blackboard System Controller.** The blackboard system solves the analytical problem by dividing it into several small problems. The optimization of the solutions for these subproblems will lead to an optimized solution to the entire problem. The control system can consult the knowledge sources and activate their corresponding unit robotic operations. These activated unit operations make up the subplan. This control flow will be continued until all subplans are complete.

A general blackboard system can be set up by combining the knowledge sources and control system together. The blackboard system diagram is shown in Figure 2. The knowledge base contains four knowledge sources. These knowledge sources cover sampling, measuring, data interpretation, and robot operation. The control system can adjust its subplan by consulting knowledge sources as well as modifying the priority of each unit operation according to the user's input. The blackboard system diagram is summarized in Figure 3.

```
[start]  define a sub-goal

generate analytical procedures

establish priority order of procedures

retrieve and display unit operations

assemble highest priority procedure

execute the procedure

test to see if all sub-goals met

return to [start] if not done

[Else] interpret and report results
```

**Figure 3.** Blackboard system control flow.

**Table II.** Fundamental Robotic Procedures

| unit operation | fundamental robotic procedure |
|---|---|
| weighing | weigh.sub |
| dispensing | transfer.sub, dilution.sub, mix.sub |
| dilution | dilution.sub, mix.sub |
| liquid/liquid extraction | transfer.sub, mix.sub |
| measuring | measure.sub |
| titration | titrate.sub |

## EXAMPLE BLACKBOARD APPLICATION

To show how the blackboard system works, we will detail the analysis of a water sample that contains $Co^{2+}$, $Cu^{2+}$, and $Ni^{2+}$. In this experiment, we use a UV/VIS spectrophotometric method. Table I lists several basic unit operations that are required for the analysis. Table II shows the fundamental robotic procedures required.

The first step in the analysis is sample preparation. To process this step, information from both the user as well as sampling and measuring knowledge sources is required. A sampling subgoal can be formed. To accomplish this subgoal, the system will optimize it by rearranging the sequence of the robotic procedures according to their priorities. This arrangement is done by modifying the conditions of the subplan using the sampling and measuring knowledge sources.

In this sampling process, several procedures are generated for consideration, they are (a) Weigh.Sub, (b) Clean.Sub, (c) Dilution.Sub, (d) Transfer.Sub, and (e) Mixing.Sub. The analysis conditions are (a) the sample is solution; (b) the metal ion in the sample is copper; (c) the standard solution is not prepared yet; and (d) the measuring cell for UV/VIS measurement is clean. These conditions are represented in the system as follows

```
EXECUTE THE PROCEDURE:

    condition -- sample(solution)    [sampling]
      activate -- transfer.Sub

    condition -- sample(ready)       [measuring]
      activate -- measuring.Sub

    condition -- standard(not yet)   [sampling]
      activate -- standard.Sub

    condition -- standard(ok)        [measuring]
      activate -- measuring.Sub

    condition -- get data            [interpret]
      activate -- interpret

    condition -- out of range        [interpret]
      activate -- dilution.Sub
                  mixing.Sub
                  transfer.Sub

    condition -- sample(ready)       [sampling]
      activate -- measuring.Sub

 repeat until all sub-goals are achieved

 interpret and report results
```

**Figure 4.** Process of the chemical analysis by the blackboard system (sample conditions I).

condition = sample(solution)
condition = ions(cu + 2)
condition = standard(not yet)
condition = cell(clean)

Based on these conditions, one of five following robotic procedures (a) Weigh.Sub, (b) Clean.Sub, (c) Dilution.Sub, (d) Transfer.Sub, and (e) Mixing.Sub will be selected by the system according to their priorities. The relative priority sequence is as follows:[10] (a) 0, (b) 0, (c) 0, (d) 1, and (e) 0.

The reason that the priorities are limited to 0 or 1 is that every task must have only one status; it is to be executed or not. In the use of this expert system, several rules might be invoked at the same time because they adequately meet the requests of the system. There are various schemes for conflict resolution.[11] In this system, recency order is sufficient because of the limited scope of the knowledge base. Recency order depends on the order of the rules in the knowledge base and simply means that the most recently implemented rule will be chosen when equivalent choices are available. Therefore, the important rules or recently updated rules are listed at the beginning of the knowledge base. This provides a simple way to simulate opportunistic reasoning.

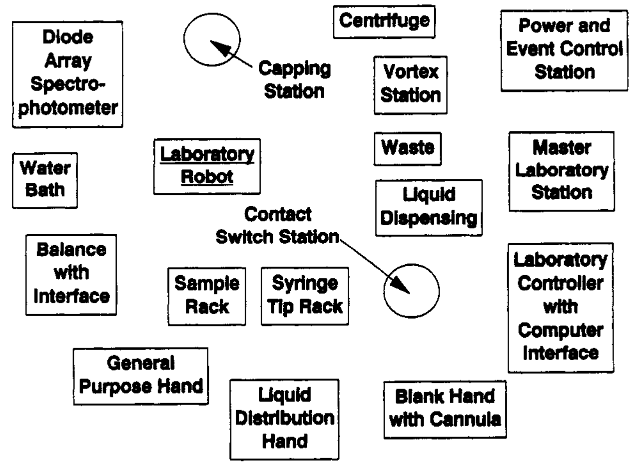


**Figure 5.** Layout of laboratory robotic system.

Based on the priority of the task, the blackboard system will place the procedure "transfer.sub" as the first procedure in the sampling subplan. After the sampling subgoal is achieved, the system will solve the next subproblem it encounters. Once all the subgoals are achieved, it will report the results. Figure 4 shows how the blackboard system activates and executes the analysis. In the second step of the analysis, the condition changes to "sample is ready to measure". This change triggers the system to consult its knowledge sources again and use the updated conditions to form a new subplan, measure. The "measuring.sub" results in achieving this subgoal. This process continues until all the subgoals are satisfied, including reporting the results.

## EXPERIMENTAL SECTION

**Robotic System.** A Zymate II robot was used to perform all the experimental manipulations. The robotic system included a robot arm with three removable hands, a vortex mixer, a solvent delivery system, a balance, and a centrifuge. The diagram for the laboratory robotic and the UP UV/VIS spectrophotometer is shown in Figure 5. The Zymate controller was used to communicate between the Zymate II and the microcomputer.

**Microcomputer.** An IBM PC running under MS-DOS 3.3 operating system and equipped with one 360K floppy disk driver, one 20 Mybte hard disk, and 640K of RAM was used for this work.

**Spectrophotometer.** An HP 8451 diode array spectrophotometer with a wavelength resolution of 4 nm over the range from 190 to 820 nm was used to collect all UV/VIS absorbance spectra.

## RESULTS AND DISCUSSION

The blackboard system was implemented with a PASCAL program. The blackboard system could be implemented in any highly structured programming language. PASCAL was used to take advantage of PASCAL communication routines already in use in our laboratory.

The user interface allows the user to input the information required by the system to design an analysis procedure. The more information the user provides, the easier this process will be. The design of this user interface relies heavily on general expertise in analytical chemistry. The entire information query process may be considered a tutor for designing analysis procedures.

The details of the information query process will, in general, be different depending on the particular environment. However, this system provides a general framework for building a flexible control system in any laboratory environment.

```
*    condition -- sample(solid)          [sampling]
       activate -- weigh.sub
*    condition -- sample(solution)       [sampling]
       activate -- dilute.sub
*    condition -- cell(dirty)            [sampling]
       activate -- wash.sub
     condition -- sample(ready)          [measuring]
       activate -- measuring.Sub
*    condition -- ion(unknown)           [interpret]
       activate -- interpret(ion(Cu+2))
     condition -- standard(not yet)      [sampling]
       activate -- standard.Sub
     condition -- standard(ok)           [measuring]
       activate -- measuring.Sub
     condition -- get data               [interpret]
       activate -- interpret
     condition -- out of range           [interpret]
       activate -- dilution.Sub
                   mixing.Sub
                   transfer.Sub
     condition -- sample(ready)          [sampling]
       activate -- measuring.Sub


  repeat until all sub-goals are achieved
  interpret and report results
```

**Figure 6.** Process by the chemical analysis by the blackboard system (sample conditions II).

Normally, several alternative methods are available for the analysis of a given substance. In laboratory robotics, alternative methods are rarely set up and tested because of the difficulty in doing so. The blackboard control system can solve this problem by breaking the robotic application into several manageable subplans. These subplans can be used to find the best alternative procedures more easily. It should also be noted that these subplans are all assumed to contain only tested procedures.

The query process for chemical analysis will generally include sample state, sample amount, solvent, pH values, sample stability, possible sample content, and apparatus availability. System default values for each request are supplied by the system. Different information input for the same sample may result in a different robotic procedure. (See Figures 4 and 6.) The differing conditions for the same unknown sample are shown below.

| sample conditions I (Figure 4) | sample conditions II (Figure 6) |
|---|---|
| condition = sample (solution) | condition = sample (solid) |
| condition = ions (cu + 2) | condition = ions (unknown) |
| condition = standard (not yet) | condition = standard (not yet) |
| condition = cell (clean) | condition = cell (dirty) |

The different processes resulting from the conditions above may be noted by comparing Figures 4 and 6. Those features in Figure 6 that differ from those of Figure 4 are marked with an asterisk.

The primary advantage of the blackboard system is in terms of its flexibility. That is, the ability for the user to examine alternative analytical procedures with a minimum of effort. Generally, different analytical methods for the same analysis will result in different accuracy and precision. When choosing alternative methods for the same analysis, the user should be prepared to supply the necessary information concerning the precision of the alternative methods.

The time differential between programming with more traditional methods and the methods proposed is hard to estimate. The traditional way is to design a procedure that is dedicated to a particular robotic application. The blackboard system allows different robotic applications to share procedures. So, technically, the use of the blackboard will reduce the design effort for complicated, multistep robotic applications.

All experiments were performed using a generic robotic system. Therefore, every procedure activated by the blackboard system would take the same amount of time as with traditional control methods. As noted above, the most significant advantage of the blackboard method over traditional control methods is flexibility. Eventually, the highly structured system proposed, based on the blackboard strategy, allows the user to update knowledge and data base entries as required.

## CONCLUSION

Traditional robotic programming features restrict the application of laboratory robots. The blackboard control system offers a dynamic control strategy that allows the robot to solve the problem with various alternative methods without human intervention.

The ability to select alternative subtasks within a procedure makes the blackboard control strategy a very flexible design strategy. Since proposing the "analytical director", several functions have been developed to enhance this system. The blackboard control system is another alternative design and control strategy that has particular advantage in environments where flexibility is important.

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