Characteristics and educational advantages of laboratory automation in high school chemistry

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Abstract—This paper presents a study of automation in the high school chemical Inquiry based laboratory. Simple computer-controlled devices for automation of basic manual operations were constructed and integrated with the data collection and management systems of the Fourier-Systems Inc. in students' lab sessions. We examined characteristics of learning in the new automated laboratory environment, evaluated educational outcomes and students' attitudes.

Keywords— chemical education; constructivist learning environment; laboratory automation; inquiry based learning; learning by doing; attitudes survey.

I. INTRODUCTION

Rapid development of automation technologies cardinally changes experimentation in chemistry research laboratories [1]. Information management systems automate collecting and analyzing data of chemical experiments and communication of results, thereby freeing laboratory staff from routine operations.

Laboratory automation courses have been introduced in undergraduate and graduate chemistry curricula [2]. A number of papers report on applying industrial titrators [3] or constructing an automated titrator based on industrial automated devices, such as an automated pipette [4], a metering pump [5], or a computer-controlled syringe pump [6].

Recently the automation trend has involved high school chemistry laboratories. In Israel the Advanced Chemistry discipline includes a unit called "Inquiry Based Laboratory" [7]. To study the unit, many school laboratories are equipped with a computerized system which provides students with automation of experimental data collection and analysis by means of sensors, data loggers and computers [8]. Educational studies indicated the positive effect of this practice on fostering higher order thinking skills of the students.

In this study we designed an automated titrator and a computer controlled dispenser and followed up their use by high school students in chemistry laboratory experiments. The Student Learning Environment Inventory (SLEI) [9] was employed in order to examine students' perceptions of a learning environment which integrates the automation devices in basic chemical experiments.

II. AUTOMATION SYSTEM DEVELOPMENT

While in the conventional chemistry laboratory experiment the learner deals with the reactor and reagents directly, in the computerized laboratory [8] this connection is mediated by the technological chain: learner – computer – data logger – sensors – reactor – reagents. This chain provides the learner with automated data collection and processing.

In this paper we propose to make the next step in automation of the school chemistry laboratory – to integrate the computerized laboratory with devices providing automation of manual operations. Introducing the automated devices enables computer controlled supply of reagents and real-time synchronization between manipulation, measurement and data collection. In this architecture the computer not only collects and processes data but also controls the automated devices, as presented below.

A. Devices

We use the MultilogPro data logger connected to PC, or the NOVA 5000 computer with built-in data logger, both of Fourier Systems (www.fourier-sys.com). The sensors of Fourier and Vernier are applied (www.vernier.com).

The automated devices have been developed using the modular robot construction kit Robix (www.robix.com) and other mechanical, electronic, and laboratory components. These devices are driven by the servo motors which are connected to the host computer through the electronics interface. The software supports a script language for generating point-to-point motion sequences. In this paper we describe two automated devices developed in our study: a computer controlled dispenser and an automated titrator.

B. Computer Controlled Dispenser

Taking aliquots by the Moore pipette requires time, high attention and manual skills, the lack of which causes errors in students' experiments [10]. We developed and implemented a simple automated dispenser (see Figure 1). The device is a slider-crank mechanism constructed out of a servo motor, plastic rail B, syringe C, and tip D. The servo motor uses this mechanism to move the syringe piston in order to take the aliquot. The motor is controlled by computer through the Robix electronics interface F.
The user can define by coordinates initial and final positions for the syringe piston movement that provide taking the needed aliquot volume. In our experiments we programmed the dispenser for taking 1 ml aliquot, providing complete filling and evacuation of solutions from the tip.

C. Automated Titrator

The automated titration system consists of a constant delivery rate titration device, stopcock, capillary injector, NOVA 5000 computer and sensors, as presented in Figure 2.

The constant delivery rate titration device consists of the air pump, air reservoir, and titrant tank. The air pump provides the air reservoir with 104.0 kPa constant pressure which is safe for students' experimentation (102.6% of the normal atmospheric pressure). The titrant tank is connected by a silicon tube to the pressure source - air reservoir. Another silicon tube is submerged in the titrant solution and connected through the stopcock to the capillary injector. The air pressure extrudes the titrant solution from the tank to the capillary injector when the stopcock is open. During the titration process the capillary injector (inner diameter 0.1 mm) injects the titrant to the reactor, being submerged in the titrated solution. This is done in order to avoid "drop error" effects [11]. The titrant solution is not flowing into the reactor when the capillary injector is submerged in the titrated solution and the stopcock is closed. All the components of the automated titration system, except the NOVA 5000 computer and sensors, are developed or modified by the authors. One of the technical problems was to synchronize the moments of opening the stopcock and beginning measurements by pH and/or conductivity sensors. The simultaneous start of injecting the titrant and data collection in the experiment is achieved using the indicator - a simple electronic circuit consisted of a push button switch, a battery, and a voltmeter sensor connected to NOVA 5000. At the moment of manual turning on the tap of the stopcock, it releases the push button switch, thus breaking the circuit. The voltmeter registers the resulted voltage fall and sends the input signal to NOVA 5000 operating standing in the triggering run mode. When receiving the input signal NOVA 5000 starts sensor measurement and data processing.

The automated titration procedure is as follows:

- To take aliquot of the titrated solution by the computer controlled dispenser to the beaker and add distilled water.
- To submerge the pH sensor and injector into the titrated solution (in the beaker) and turn on the stirrer.
- To run the data collection program on NOVA 5000 and turn on the stopcock.
- To follow up the screen representation of the titration process and detect the equivalence point.
- To stop the program, close the stopcock, take out and wash the pH sensor and injector.

The graph of titration displayed on the screen is presented in Figure 3. After determining the equivalence point from the pH derivative graph and the titration period from the voltage graph, the titrated solution concentration is calculated.
- Human errors (misjudging the color of the indicator near the end point, misreading the volume, lack of skills of using burette and pipette, incorrect meniscus leveling.

### III. IMPLEMENTATION AT SCHOOL LABORATORY

The described automated devices were used for teaching the Case-Based Computerized Laboratory subject as part of the Chemistry course for secondary schools. The subject was taught in 2006-2007 school year to eleventh grade (N=30) and twelfth grade (N=24) students. Both groups studied and conducted titration experiments in which data collecting and analysis were automated by the data logger system, while titration manipulations were performed in two modes: manually and with the automated titrator and dispenser.

The laboratory work in the manual and automated modes was compared by means of chronometering titration manipulations, as shown in Table 1. The data in Table 1 indicate that using the automated devices significantly reduces time needed for performing titration laboratory work. When taking aliquots by means of the automated dispenser the student does not need to concentrate on coordination of her/his visual perception and hand operation in order to fix the meniscus at eye level. The operation of filling the burette in the automated mode is omitted and thus, many errors typical for inexperienced students are avoided. In the automated mode there is no need to perform the first "rough" titration as required in the manual mode.

Table 1. Chronometering titration laboratory (in minutes)

| Operation                  | Manual manipulation | Automated manipulations |
|----------------------------|---------------------|------------------------|
| Taking 3 aliquots          | 10                  | 3                      |
| Filling the burette (3 times) | 5                   | 0                      |
| Titration of the first aliquot | 10                  | 3                      |
| Titration of second and third aliquot | 10                 | 6                      |
| Calculating the result     | 10+ at home         | 10                     |
| Total                      | 45                  | 22                     

Our goal in introducing automated titration was twofold:
1. To save laboratory time spent for manual operations and use it for activities focused on better understanding of the subject matter.
2. To increase students' motivation to study chemistry through experimentation by providing them with an advanced learning environment that integrates modern computer-based automation technology.

To address the first goal we compared students' activities performed in the computerized laboratories with and without automated devices. The activities during 45 minutes of the lesson without automated devices are listed in the second column of Table 1. As follows from the third column of the table, the same work with automated devices took only 22 minutes. The students used the extra time for inquiry activities required by the curriculum of the advanced level chemistry laboratories [7]. Accordingly, each group of students has to formulate at least five research questions related to the studied phenomenon, discuss them and plan their own new experiment aimed to answer one of the questions. In the discussions with participation of the teacher the students considered different aspects of the phenomena, some of which were beyond the curriculum. In contrast, the groups that conducted the titration experiment manually had to leave the inquiry activities for the next laboratory lesson.

In 2007-2008 the subject was taught to the twelfth grade class of 36 students with titration experiments conducted in the manual and automated modes. We evaluated the effect of introducing the automated devices on students' motivation to study chemistry by means of the post-course questionnaire which consisted of two parts. The first part was the actual version of the Science Laboratory Environment Inventory (SLEI) [9].

This questionnaire examined students' attitudes towards the laboratory environment. The SLEI questionnaire consists of 35 items grouped in five categories presented in the first column of Table 2. The second column includes sample items for each of the categories. The level of agreement with each of the items is responded on the five-point scale: 1 = Almost Never, 2 = Seldom, 3 = Sometimes, 4 = Often, 5 = Very Often.

Table 2. Scales and sample items of SLEI.

| Category                  | Sample Item                                                                 |
|---------------------------|-----------------------------------------------------------------------------|
| Student cohesiveness      | Students work cooperatively in laboratory sessions.                         |
| Open-endedness            | In our laboratory sessions, different students do different experiments     |
| Integration               | The laboratory work is unrelated to the topics that we are studying in our science class |
| Rule clarity              | Our laboratory class has clear rules to guide student activities            |
| Material environment      | The equipment and materials that students need for laboratory activities are readily available |

We analyzed the students' attitudes through comparison of our results with other studies [7,9,12,13], in which different types of chemistry laboratory environments in Israeli high schools were evaluated using the SLEI instrument. Hofstein et al. [9] considered a close-ended laboratory without computers, inquiry activities and automation. Attitudes towards the inquiry based laboratory were examined by Hofstein et al. [1], and towards the case-based computerized laboratory by Marjiah [13]. The mean grades assigned to the five categories of the SLEI in our study and in the three abovementioned studies are presented in Table 3.

The table indicates that the evaluations of our chemistry laboratory environment in all the categories, except one (Integration), are higher than of the other environments.
Table 3. Results of the SLEI test in our and other studies

| SLEI categories | Lab Type       | Close-ended lab [8] | Inquiry lab [11] | Case-based computerized lab [12] | Our results [13] |
|----------------|---------------|---------------------|------------------|----------------------------------|-----------------|
| Student cohesiveness | 3.80          | 3.87                | 3.90             | 4.25                             |
| Open-endedness    | 2.20          | 3.27                | 2.57             | 3.47                             |
| Integration       | 4.20          | 4.08                | 3.70             | 3.41                             |
| Rule clarity      | 3.62          | 3.69                | 3.74             | 3.85                             |
| Material environment | 3.55          | 3.71                | 3.88             | 3.87                             |

The lowest evaluations were given to the close-ended laboratory [9]. A possible explanation for higher evaluations of the automated environment is that it reduces time needed for the experiment and utilizes it for further inquiry activities. It combines advantages of computerized data collection and analysis, automation of manual operations and self-directed experimentation.

The mean grade for the Integration category given to our laboratory is lower than to other laboratories possibly because in our case chemistry laboratory was studied following the new curriculum which did not provide coordination between laboratory sessions and related theoretical studies.

The questions in the second part of the survey tested students’ degree of consent with the assertions related to using the automated devices. The following eight assertions were extracted from interviews with the students who had participated in our study in 2006-2007:
- The experiment aided by the automated devices is more rapid.
- The use of automated devices yields more accurate results.
- The experiment with application of the automated devices is similar to an industry laboratory test.
- Practice with the automated devices allows the students to acquire skills important for their future careers.
- The experiment by means of the automated devices is more convenient to perform.
- Integrating the automated devices creates opportunities for students’ participation in planning their laboratory activities.
- The automated devices make the experiment safer.

Students’ opinions about these assertions are summarized in Figure 4. The diagram shows high positive evaluation of using the automated devices by the students. The fact that the highest evaluation 4.5 (out of 5) was assigned to the importance of using advanced technology devices points to the attractiveness of the laboratory automation. The majority of students noticed that experiments with automated devices are more convenient, rapid, accurate, safe, and impart skills of working in automated environments. With this, high positive results give the comparatively lower evaluation of the third assertion reflects that the students do not associate the developed devices with that used in industry laboratory.

Figure 4. Evaluation of using automated devices

These findings are in line with students’ reflections collected by interviews. A typical student’s response:

“In the automated laboratory receiving titration was more simple and faster as compared to the manual experiments, our preference is certainly, performing titration with convenient automated equipment”.

In the interviews the students also noted that the automated titration experiment is more simple and significantly faster, experimental results in this mode are more accurate because the control is not by eyeballing. The students were very positive about automation of manual operations in their laboratory practice. Many of the students expressed interest and motivation in studying automation and participation in designing and building automated devices.

IV. IMPLEMENTATION OF THE AUTOMATED LABORATORY IN 2009-2010. COMPREHENSIVE URBAN HS CASE

We equipped the school chemistry laboratory with eight automated titrators. Each titrator includes NOVA 5000, Fourier sensors, magnetic stirrer, and self-made constant delivery rate device. The automated titrators were used for experimentation of 11th and 12th grade students in the framework of laboratory study unit (N=101). The students investigated sedimentation processes using the conductivity sensor. At the beginning, they got familiar with the automated titration system. Four interested students got special training and served as teaching assistants, explaining the device’s structure and operation rules to their peers. Then all the students performed titrations in groups of 2-3. The workplace of each group was equipped with one of the automated titrators. The titrant delivery rate at each titrator was set different from the others, in order to provide unique results in each group.

The students determined the titrant's solution delivery rate and calculated precision. The measurements of weight and volume were made by analytical balance and graduated cylinder. Their accuracy was compared using a function of Excel that was new to the students. The second experiment determined the
concentration of titrant by titrating aliquots of standard solution. Then the students conducted their own studies using the automated titrators. They formulated research questions, planned related experiments, prepared an order for the needed equipment and reagents, performed the experiments by teacher's permission, processed the received data, discussed the results in the group, and wrote the final report.

**Students' Reflections on the Automated Laboratory**

✓ “The purpose of the lab is to teach us for future "real world". Therefore, equipment should be more modern and it seems like we’ll use the devices in the future.”
✓ “Automation devices cut down the labor process, helped to the research...”
✓ “Use of automated instruments has contributed to understanding the experimental material”
✓ “There is no problem with them and can be used”
✓ “Using automated instruments helped in many implementations, shortened the time and increased the efficiency of the process of experiment”
✓ “Needs to improve, sometimes not working well”
✓ “It was hard to understand, only after a detailed explanation of the teacher could use”
✓ “Automation makes the experiment more difficult to perform ”
✓ “Only facilitated the implementation of designs”
✓ “Contributed to the accurate results for all test and add to ease processes.”
✓ “Helped a lot, sometimes got stuck and made problems.”

V. IMPLEMENTATION OF THE AUTOMATED LABORATORY IN 2009-2010. VOCATIONAL HS CASE

TAMI – the largest Israel R&D center of industrial chemistry – came with an initiative to engage students of its neighboring high school in studying chemistry and motivating them towards future work in chemical industry. The challenge was to introduce chemistry studies in an unprivileged vocational high school for students majoring in mechanical technology.

Traditional methods of teaching chemistry as an academic subject were not appropriate for this group, because the students did not have prerequisite knowledge and skills for learning science.

After examining different approaches, TAMI and the high school chose one, developed by the technology group of the Technion Department of Education in Technology and Science. This approach is based on teaching chemistry through experimentation in a laboratory environment which provides automation of data collection and processing, as well as of manual operations. Based on collaboration of the three institutions and the Fourier Systems Company under supervision of Israel Ministry of Education, the industrial chemistry project arose in order to implement the proposed approach.

Curiosity to scientific and technological aspects of chemical production first became apparent during an excursion in the experimental hall of “TAMI Automation”. The use of Fourier data loggers and sensors, providing automated data processing, stimulated students' motivation to develop automated devices and conduct chemical experiments with them. For example, a number of students at the technology lessons designed and constructed computer controlled syringe pumps (see Figure 5). Then, during the chemistry classes one of the students used his syringe pipe prototype (Figure 5A) for experimental inquiry into ideal gas laws, one of other students integrated his prototype in the automated dispenser (Figure 5B).

**Figure 5. Computer controlled syringe pumps used: A. For studying ideal gas laws; B. In the automated dispenser.**

VI. CONCLUSION

Our experience of creating simple affordable automated devices, their integration with a data logging system and teaching automated laboratories indicates the considerable potential of this technology for improving experiential chemistry education in high schools.

Application of the developed devices enables to save time spent for performing manual operations and focus the laboratory on inquiry activities. It also enables to raise the accuracy and safety of the experiments by eliminating errors and incidents related to manual operations.

The educational study showed laboratory automation as an important factor for motivating students to learn chemistry through experimentation. Results of the SLEI test in our study provide first indications that the integration of the automated devices contributes to positive attitudes towards the laboratory environment. The students certainly prefer laboratory environments which exploit modern technology. Based on students' feedback, we hope that further educational benefits can be achieved by introducing additional automated devices and through involving students in their creation. Our cases show that chemistry can be effectively taught through
experimentation in an automated laboratory in comprehensive and vocational high schools, to high and low achieving students.

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