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Review

Role and review of educational robotic platforms in preparing engineers for industry

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Abstract: Recent advances in robotics, specifically in the industrial sector, have highlighted the need to have sophisticated educational and training platforms. The cross-disciplinary nature of robotics demands industrial engineers to acquire knowledge and practical exposure of engineering, computer science and mathematical modelling. Scientists and engineers have succeeded in developing state-of-the-art academic and vocational frameworks to catch up with these advancements. This paper presents a systematic, up-to-date survey of manipulator-based frameworks with a focus on teaching and training of kinematics, dynamics and controls. Here, both virtual tools and platforms employing a real robotic arm are reviewed. These two classes of the framework are discussed to bring forth their benefits and constraints. The study also comments on the contribution of IT to aiding educational robotics. It is an attempt to provide a result-oriented review for both classes. It has been presented in a comparative manner so as to readily assist the readers to choose a robotic simulator/real platform as per their requirements. It is expected that the results of this research will be directly valuable to industrial engineers, vocational trainers, researchers, procurement officials, courses instructors and hobbyists.

Keywords: educational robotic platform, industrial training, manipulator arm, robot modelling and control

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INTRODUCTION

In recent years the domain of robotics has evolved incredibly, extending the associated applications beyond expectation [1]. Application areas of robots include but are not limited to fields in industry [2], medicine [3, 4], cognition [5, 6], space [7], underwater exploration [8] and nuclear power plants [9]. The robots employed in the industry offer several benefits in terms of optimisation of product cycle time and manufacturing cycle time [10, 11]. This advancement has resulted in the deployment of robots in various tasks including welding, packaging and arranging, cutting, paint spraying, sanding and target tracking [12, 13]. The trend in employing robots to automate traditional industrial processes has necessitated the need to address the educational and training aspects of robotics because it is a rather difficult task, particularly for a newcomer, to grasp the range of principles underlying the subject matter. This, in turn, demands sophisticated robotic platforms specifically realised for educational and vocational purposes, which in some degrees should reflect the requirements and constraints of the actual industrial scenario [14]. Given the broad interdisciplinary nature of robotics, these academic tools essentially play a vital role in bridging the gap between theoretical knowledge and practical work [15]. Engineering students who have been trained using robotic frameworks will be equipped with 'learning by doing' capability. This directly enhances their productivity when employed in an industrial sector.

The locomotion system [16] of a robot can be based on links [17, 18], wheels [19, 20] or tracks [21]. Primarily, the fundamental human-like feature of current industrial robots is their ability to move arms [22, 23]. The programmed sequence of movements results in task accomplishment. The whole scenario involves developing arm kinematics, dynamics and a control law following a pre-planned trajectory, in addition to a workspace analysis [24]. With this scenario in consideration, a number of virtual as well as real robotic platforms have been proposed by the research community. The present review is aimed at introducing these platforms with a focus on articulation-based manipulators with multiple degrees of freedom (DOF). The review is built upon the authors' experience of a decade or so in developing sophisticated educational and research platforms [25-27] involving novel robotic devices [28-31] and modelling robots [32-34]. For example, Autonomous Articulated Robotic Educational Platform (AUTAREP), shown in Figure 1, is an open-source framework based on 6 DOF, which is a fully-actuated robotic manipulator [35]. The arm comprises 5 revolute joints with a single DOF for each joint except the wrist, which is actuated in roll and pitch motions. The sensory system of the platform is composed of an onboard vision camera, a force sensing resistor for tactile sensing and position encoders. The critical parameters of the platform include a position precision of ±1.5mm, repeatability of ±1mm and payload capacity of 1kg. With a novel embedded control scheme [36], the platform has the capability to train internees in an industrial environment by validating various control strategies prior to their execution on real manipulators. The application of the proposed framework to investigating control algorithms has been presented [37, 38].

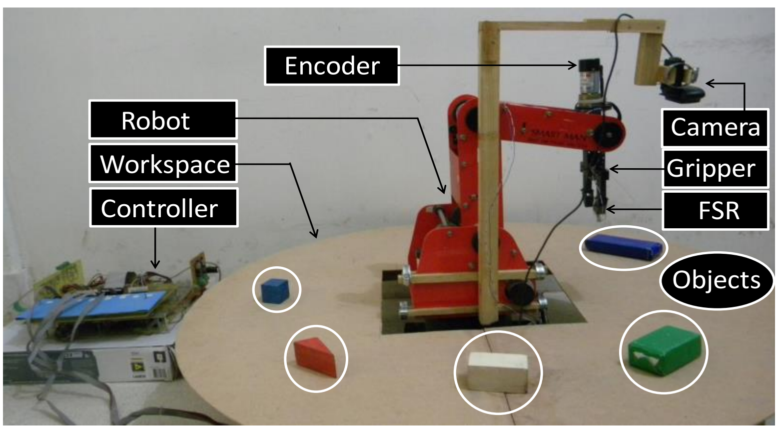

Figure 1. AUTAREP – an open-source framework with potential in academic, vocational and industrial sectors [35] (FSR = force sensing resistor)

VIRTUAL TRAINING PLATFORMS

The problem faced while teaching 'Robotics' is that it requires laboratories having sophisticated equipment, which in turn imposes constraints because of funding and maintenance. Several complicated concepts mainly related with the robot's joint motion in multi-DOF in 3D space require illustration and visualisation. The complexity of the analytical model and mapping between physical space and joint space makes it challenging for a teacher to impart robotic concepts to the students and at the same time difficult for the students to comprehend those concepts. Virtual robotic systems, offering an illustrative and cost-effective solution, find potential in explaining robotic concepts in a simple but efficient manner. Most of the recent tools provide a user-friendly graphical user interface (GUI) for interacting with the computer rather than mind-numbing keyboard commands. Furthermore, some of the tools allow users to create their GUIs based on a robotic project. Other advantages of virtual platforms include working flexibility, ease in changing simulation parameters/environment and the possibility of collaboration among multiple research groups and individual students.

The robotics community has acknowledged the increase in demand for training simulators. The reported platforms vary regarding their capabilities, ranging from visualisation of fundamental concepts like kinematics and dynamics to advanced topics like control and trajectory planning, which are explained below:

Teaching Kinematics

The problem of kinematics deals with the inter-relationship between the manipulator's joint angles and the position and orientation of an end-effector relative to the reference base frame. As an example, Figure 2 shows a kinematical representation of an AUTAREP manipulator, where frames have been assigned to each joint as per the well-known Denavit-Hartenberg (DH) parameters. The forward kinematics (FK) matrix expressing the end-effector coordinates in respect of the base of the robot is given by (1):

$$ {}^{0}_{6}T = \begin{bmatrix} c_1c_{234}c_5 + s_1s_5 & -c_1c_{234}s_5 + s_1c_5 & -c_1s_{234} & c_1A \\ s_1c_{234}c_5 - c_1s_5 & -s_1c_{234}s_5 - c_1c_5 & -s_1s_{234} & s_1A \\ -s_{234}c_5 & s_{234}s_5 & -c_{234} & B \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{1} $$

where $c_a = cos(a),\ c_{ab} = cos(a+b),\ c_{abc} = cos(a+b+c),$ and A and B are given by (2) and (3) respectively:

$$ A = -l_4s_{234} + l_3c_{23} + l_2c_2, \tag{2} $$
$$ B = l_1 - l_4c_{234} - l_3s_{23} - l_2s_2. \tag{3} $$

In contrast to the FK, the inverse kinematics (IK) problem evaluates the joint angles, given the position and orientation of the end-effector. The IK model of the AUTAREP manipulator has been derived [25].

The scientific community reports various virtual platforms for teaching kinematics. Hejase and Hasbini [39] presented a Turbo-Pascal-based graphical simulator for learning robot kinematics. The user can compute FK by a homogenous transformation matrix and joints mechanical values. The platform also offers the IK solution and the possibility of learning through a 'soft' teach-pendant. Inspired by ROBOT-DRAW [40], Manseur [41] proposed a novel virtual-platform Robot

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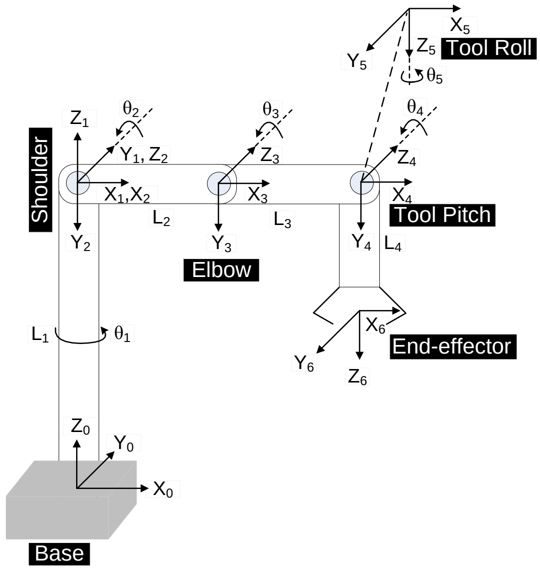

Figure 2. Schematic of AUTAREP manipulator

Modelling (RMod), which encompasses multiple capabilities including analysis and simulation of robotic manipulators prior to their design. Using the DH convention, the tool finds potential for studying and investigating the structure (and thus locomotion) of a manipulator, exploiting the divide-and-conquer approach. On the basis of the 3D graphical model of a robot structure, the virtual environment (Figure 3) offers visualisation, evaluation and simulation through an operator which specifies the joint configuration. The tool has been demonstrated to be successfully applied to the design of multi-limb robots.

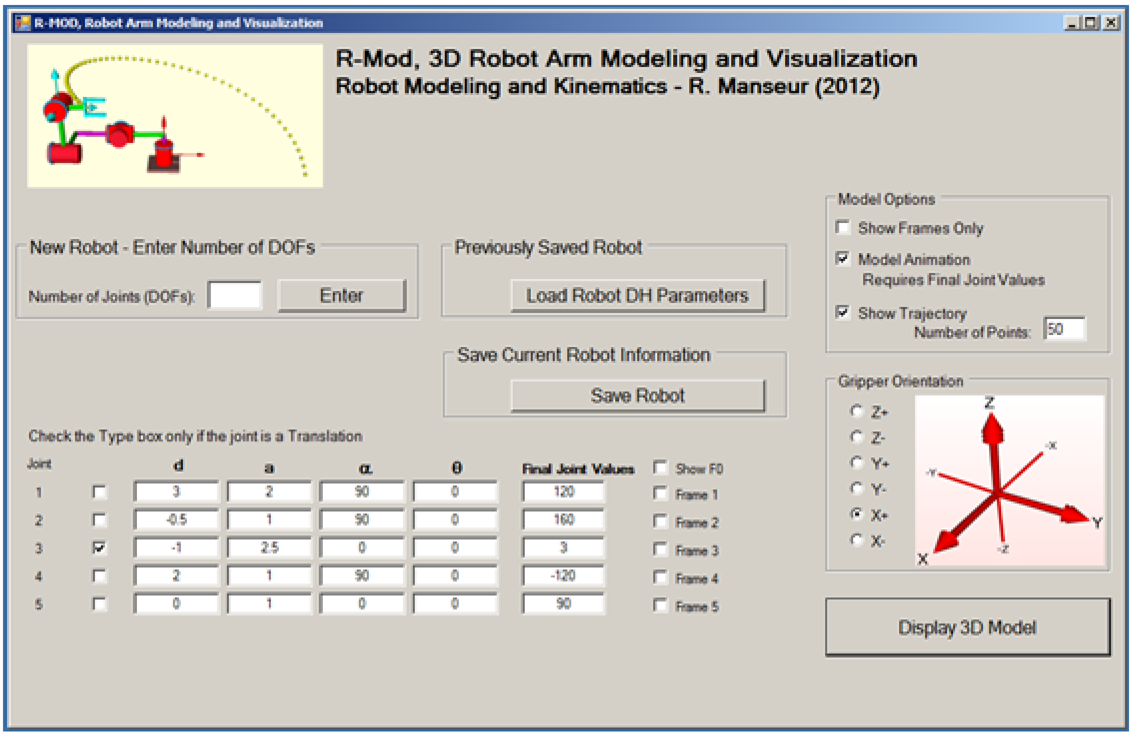

Figure 3. GUI of virtual platform RMod [41]

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Robot visualisation system (RVS) is another excellent virtual application developed by Khan et al. [42]. In addition to FK and IK, the application can be utilised for trajectory planning of an n-link manipulator. Potentially useful quantitative data of a robot, e.g. maximum reach, characteristic length, optimum posture and conditioning, is available to the user. Système de modélisation et d'animation de robots (SMAR) is another training simulator that has been developed with the aim of analysing and validating the algorithms in computer-aided design (CAD) Robotics [43]. The tool can model the collision-free path for manipulators and can compute optimal placement to perform the task efficiently. Robotech is another simulation software that can model up to 10 serial link manipulators [44]. The tool offers the possibility to design the kinematic model in three alternative formats: DH parameters, homogeneous transformation and joint-beam method. Other parameters such as range of motion, gear ratio, sensor error, sensor resolution and calibration, and actuator backlash can also be defined in the model.

Exploiting the integration of virtual reality (VR) with robotics, Yang et al. [45] developed a robotics learning system. Three virtual robots, modelled in 3D Studio Max, are used to demonstrate the concepts of FK, IK and collision detection. Another open-source platform, serial n-axis manipulators (SnAM), is aimed at modelling the kinematics of *n*-DOF serial robotic arms having any kind of architecture [46]. The closed-loop FK has been solved by using developed and highly efficient algorithms, while matrix formulation, elimination and numerical approaches determine the IK solution. 3D-RAS (robotic arm simulator), based on LabView, is another prominent educational tool for kinematic analysis of anthropomorphic manipulators [47]. The distinguishing feature of this platform is that it does not require any programming experience and supports arms with up to 5 DOF. Using DH parameters, the tool finds potential for grasping the concepts of kinematics, workspace analysis and volumetric and surface trajectories. A comparative review of simulation platforms for teaching kinematics is presented in Table 1.

Table 1. Comparative review of virtual robotic platforms (for teaching kinematics)

Framework	Developer	Environment	Features: GUI/ Dynamics/ Trajecory Planning	Robots in library	Ref.
AUB P/form	American U. of Beirut	Turbo Pascal	✓/×/×	Rhino	[39]
RMOD	SUNY Oswego, US	Windows	✓/×/✓	Generic	[41]
RVS4W	McGill U., Canada	Windows	✓/×/✓	Generic	[42]
SMAR	U. of Poitiers, France	CAD-Robotics	✓/×/✓	Generic	[43]
Robotect	OphirTech Inc., US	Windows	×/✓/✓	Serial link (actuated/constrained, prismatic/revolute)	[44]
PU P/form	Purdue U., US	C++, GLUI, OpenGL	×/×/✓	Puma 560, CRS A460, Virtual robot	[45]
SnAM	U. of Guanajuato, Mexico	C++	✓/×/✓	None	[46]
3D- RAS	U. of Huelva, Spain	LabView	✓/×/✓	PUMA560, A255, Denso VP Series, IRB2400, IRB-6, Lynx6, Pioneer 2, Bionic arm	[47]

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Teaching Dynamics and Control

Dynamics is the study of forces and moments causing the motion in a system. The dynamics of a robotic manipulator can be modelled by using Euler-Langrange, recursive Lagrange, recursive Newton-Euler, Kane's equation, D'Alembert Principle and other reported approaches based on velocity constraint matrices and divide-and-conquer approach. Newton-Euler and Euler-Lagrange methods are more common in the robotics community. The dynamics of the AUTAREP manipulator has been derived [25] using the following Euler-Lagrange method:

$$\tau = M(q)\ddot{q} + V(q,\dot{q}) + G(q), \tag{4}$$

where τ denotes the applied torque, $M(q)$ is inertia tensor, $V(q,\dot{q})$ and $G(q)$ represent Corollis forces and gravitational force respectively, and $q, \dot{q}$ and $\ddot{q}$ denote joint position, velocity and acceleration respectively.

In a robotic system a manipulator is required to carry out a particular task by moving its end-effector accurately and repeatedly; thus a control strategy is needed. Common control strategies are based on linear laws such as Proportional Integral Derivative (PID) and Linear Quadratic Regulator and modern laws such as Computed Torque Control, Sliding Mode Control and Model Predictive Control. The PID control law for AUTAREP has been derived [48] while a detailed review of control strategies for robotic manipulators has been reported [49-51]. As an example, Computed-Torque-Control-based control law for AUTAREP is:

$$\tau = M(q)(\ddot{q}_d - 2\lambda\dot{e} - \lambda^2 e + V(q,\dot{q}) + G(q), \tag{5}$$

where τ is the required control output and is represented by $\tau = [\tau_1\ \tau_2\ \tau_3\ \tau_4]^T$, q_d is the desired position of the robot joint, and $e = q - q_d$,. The gain matrix, $\lambda = \mathrm{diag}\ \{\lambda_1\ \lambda_2\ \lambda_3\ \lambda_4\}$, can be used to alter the system dynamics.

Going beyond the derivation of kinematics and visualisation through an interactive GUI, the scientific community has reported several platforms for enhancing the understanding of system dynamics and control. Over the years, Matrix Laboratory (MATLAB) has emerged as a very popular, intuitive and easy visualisation and simulation platform for demonstrating robotic concepts. However, the primary constraint in using MATLAB packages, 'SimMechanics', is their inability to simulate closed-loop feedback control systems, given the kinematics and inverse dynamics of a robot. This is one of the key motivations behind the development of a number of virtual tools for teaching robotic control. Robotica is one of the earliest dynamic platforms developed by researchers of the University of Illinois at Urbana-Champaign [52]. Encapsulating more than 30 functions in a CAD package, the open-source tool offers computations both symbolically and numerically.

RoboAnalyzer is another open-source modular platform developed with underlying concepts of object-oriented modelling [53]. It has a variety of computational capabilities ranging from IK to inverse dynamics and is designed primarily following a model-to-concept-based learning approach. The dynamics relies on a recursive dynamics simulator (ReDySim) algorithm [54]. With the focus on the simplified understanding of robot modelling, researchers at Technical University München conceived another platform [55]. The tool can compute the symbolic solution of robot regressor in closed-form. The open-source Robotics Toolbox for MATLAB [56] is probably the most common virtual tool found in the laboratory for academic and research purposes. It is a command-based tool visualised with 3D-wire. The tool offers the possibility of defining and creating robot objects by a

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variety of serial-link manipulator mechanisms. The latest release also provides vision-based control of the robot's end-effector for visual servoing. As a complement to the Robotics Toolbox for MATLAB by addressing its limitations, RobotiCad has been developed [57]. The platform includes workspace objects in Simulink model and has a dedicated script tool. The developed library contains additional functions for manipulability analysis and trajectory generation.

A novel tool for robot analysis with a focus on computer vision has been developed by Jara et al [58]. Its novelty lies in the higher number of functionalities on a single platform, which permits the development of complex simulations. This is made possible by combining an open-source tool, easy java simulations (EJS), with a high-level java library EjsRL which is specifically designed for EJS to deal serial-link manipulators, computer vision algorithms and remote operation. Zlajpah [59] presented another integrated environment for modelling, simulation and controller design of *n* DOF with revolute joints. Based on the developed 'Planar Manipulators toolbox', the promising feature of the framework is its flexibility in rapidly forming a prototype with various control algorithms, especially in the case of redundant manipulators. Another open-source platform is RobLib, which is specifically tailored for the undergraduate students [60]. It is restricted to planar manipulators with 2 DOF. Both positions, as well as force control laws, can be simulated.

BRACON is a robot control system that is formed on Python platform [61]. The free programming language provides a low-cost solution for actuator angle control, which is based on direct and inverse kinematics. The tool is designed for educational robotic arms with 6 DOF and it can be tailored according to specific requirements. Brejis et al. [62] have presented a novel MATLAB-based simulator to generate a mathematical model of serial manipulators. The novelty of the tool lies in its realism in terms of the consideration of taking friction and stiction by Lund-Grenoble dynamical friction model. ROBOSIM2 is another MATLAB-based educational tool presented by Fueanggan and Chokchaitam [63]. The simulation procedure involves three steps: inputting link masses and inertia, computing robot kinematics and dynamics followed by designing linear control law, and finally displaying the robot in a 3D environment (Figure 4).

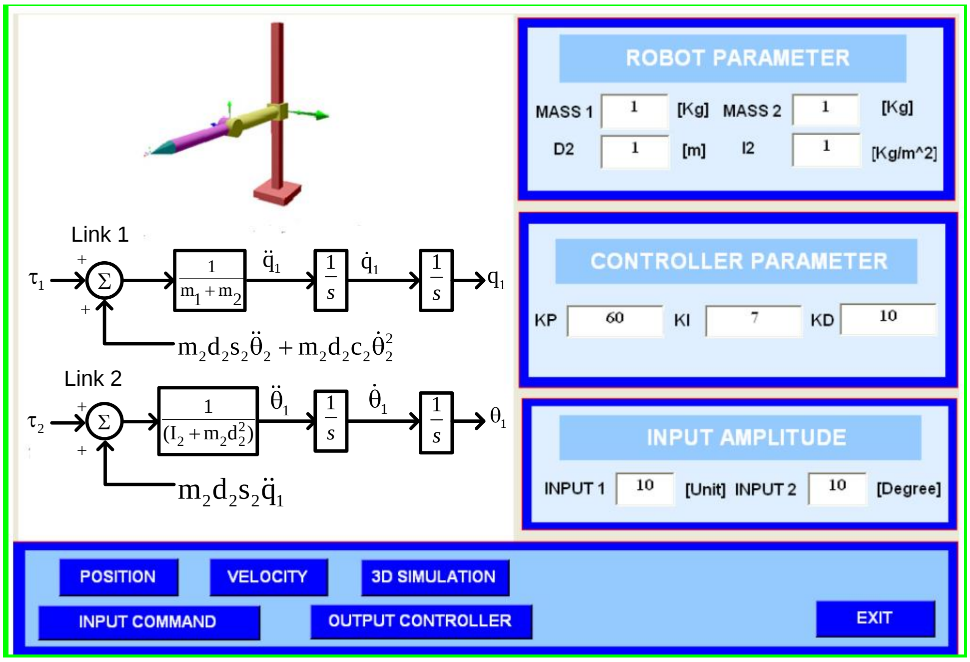

Figure 4. Typical GUI of a platform for teaching PID control [63]

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Other examples of robotic platforms used for teaching dynamics and control include ROBOTLAB [64], HEMERO [65], Virtual Robot Experimentation Platform (V-REP) [66], Arm6x [67] and ROBOLAB [68]. Their comparative review is presented in Table 2. Quite a large number of the platforms are based on MATLAB/Simulink, while platforms based on other tools like Visual C#, OpenGL, Java, Borland Delphi, Mathematica, Simnon, LISP, etc. are also reported. The dynamics of the platforms can usually be derived under Newton-Euler (N.E) or Lagrange (L).

Table 2. Comparative review of virtual robotic platforms (for teaching dynamics and control)

Framework	Developer	Features: GUI/ Trajectory palnning/ Control	Robots in library	Dynamic algorithm	Ref.
Based on MATLAB/Simulink					
ReDySim	Indian Inst. of Tech. (IIT), Delhi	✓/✓/✓	Generic	DeNOC	[54]
Technical University München Platform	Technical U. München, Germany	✓/×/✓	Generic		[55]
CorkeToolBox	Peter Corke	×/✓/✓	Serial manipulators	N.E	[56, 69]
RobotiCad	U. of Bologna, Italy	✓/✓/✓	Cartesian and serial robots	N.E/L	[57]
Planar Manipulator Toolbox	Inst. Jožef Stefan, Slovenia	×/✓/✓	Planar manipulators (*n* revolute joints)	L	[59]
Delft University of Technology Platform	Delft U. of Technology, Netherland	✓/×/✓	16 robots each with 6 DOF		[62]
ROBOSIM2	Thammasat U., Thailand	×/×/✓	R, RR, P, PP, RP, PR (R=Revolute, P=Prismatic)		[63]
ROBOTLAB	Federal U. of Paraíba, Brazil	×/✓/✓	Generic	N.E	[64]
HEMERO	U. of Seville, Spain	×/✓/✓	PUMA 560	N.E	[65]
Arm6x	Concurrent Dynamics International	× /× /✓	None	N.E/L	[67]
ROBOLAB	U. of Kocaeli, Turkey	✓/✓/×	PUMA, Stanford SCARA, Prismatic and all possible configurations (16 default robots)	N.E/L	[68]
Based on other tools					
Robotica	U. of Illinois at Urbana-Champaign, US	✓/× /✓	None	L	[52]
EJS + EjsRL	U. of Alicate, Spain	✓/✓/✓	Multiplatform support	N.E	[58]
RobLib	Inst. of Engineering of Coimbra, Portugal	✓ /✓ /✓	RP, RR (R=Revolute, P=Prismatic)	N.E	[60]
V-REP	Coppelia Robotics, Germany	✓/ ✓/ ✓	Generic	ODE, Bullet, Vortex	[66]
RoboAnalyzer	Indian Inst. of Tech., Delhi	✓/✓/×	PUMA 560, Stanford arm and KUKA KR6	DeNOC	[70]

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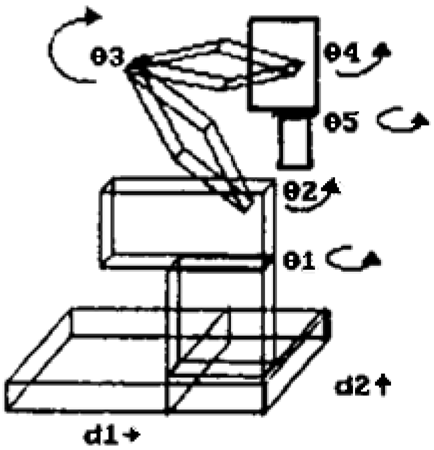
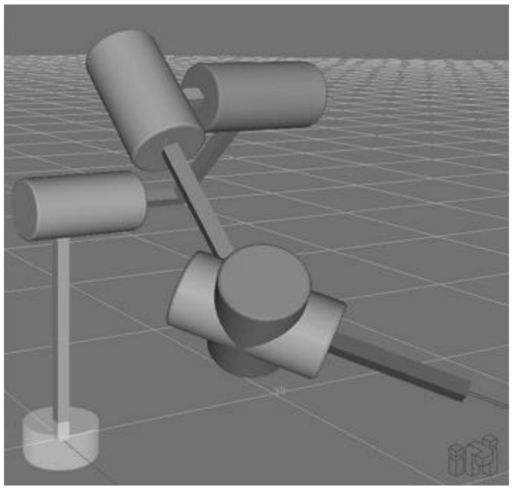
IT SUPPORT FOR EDUCATIONAL ROBOTICS

Historically, the developments in VR and CAD were independent of each other [71]. However, later on the integration of advances in both of these domains resulted in the realisation of interactive, intuitive and user-friendly virtual modelling simulators. This integration has significantly replaced conventional static 2D views with the corresponding 3D visualised environments. This trend has significantly influenced robotic simulators as well. Improvements in the robot's modelling and rendering style, visualising trajectory, generating workspace, creating user-friendly GUIs and intuitive animations are all the results of incorporating VR and CAD in robotic platforms and advances in computer vision processing tools. VIGRA, open computer vision (Open CV) and VXL are outstanding libraries that have been developed specifically for academic and research activities. Figure 5(a) shows a simple 2D model of American University of Beirut platform reported in the early 1990s [39]. On the other hand, Figure 5(b) illustrates a sophisticated 3D model of SnAM framework [46].



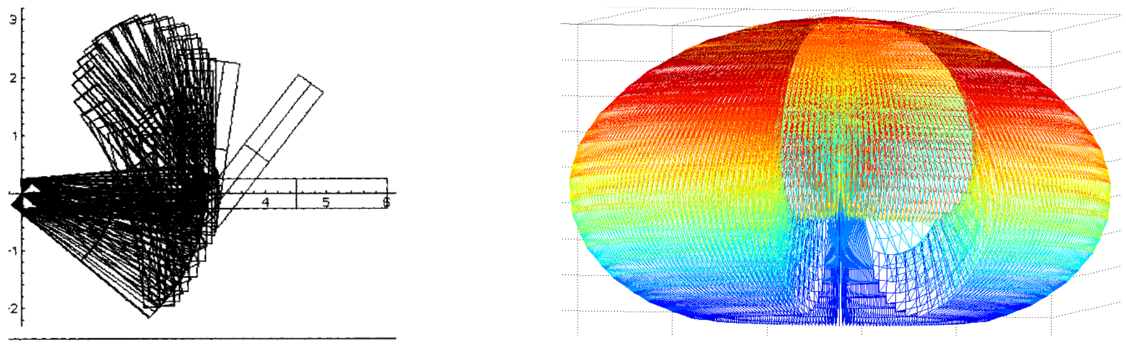
(a)



(b)

Figure 5. (a) 2D model of American University of Beirut platform; (b) 3D model of SnAM framework [46]

Various IT tools have been devised in order to help educational robotics. Simderella, an open-source tool reported in the early 1990s, was developed primarily to speed up the design of robot controller interfaces by offering formulation and direct testing of new control laws [72]. RoboWorks, developed by Newtonium Inc., uses simple 3D primitives for the construction of articulated objects [73]. The objects described in nodes are based on a scene graph approach. Extending the capabilities of Simderella and RoboWorks, virtual-robots (VROBO) is another software for facilitating modelling and simulation in educational robotics [74]. Its distinguishing features include reduced cost and lesser complexity, increased flexibility and portability, and enhanced network capabilities. RVS [75] and robot visualisation system for Windows (RVS4W) [42] are open-source 3D visualisation applications which are used in the feasibility analysis of a new robot or a newly planned path. The programs create a skeleton which is based on the DH-chart and also offer the possibility of elaborate rendering. Other relevant examples include robotics illustrative software (RIO) [76], robot off-line programming and simulation (Ropsim) [77], Easy-Rob [78] and interactive graphics robot instruction program (IGRIP) [79]. The impact of IT revolution on the robot's workspace generation can be observed in Figure 6. Figure 6(a) shows the workspace of Robotica which was developed in 1994. The simulated workspace is in 2D and has very rough edges. On the other hand, the workspace of AUTAREP was created using modern tool (MATLAB) and it provides 3D visualisation with better resolution and graphics.



(a) (b)

Figure 6. Simulated workspace of (a) Robotica [52] and (b) AUTAREP [25]

The advancement in IT has also facilitated the development of interfaces for hardware educational platforms. Features like menus, icons, dialogue boxes and prompt messages offer user-friendly human-robot interaction through the keyboard as well as mouse. Figure 7 illustrates the main window of GUI that is developed for AUTAREP.

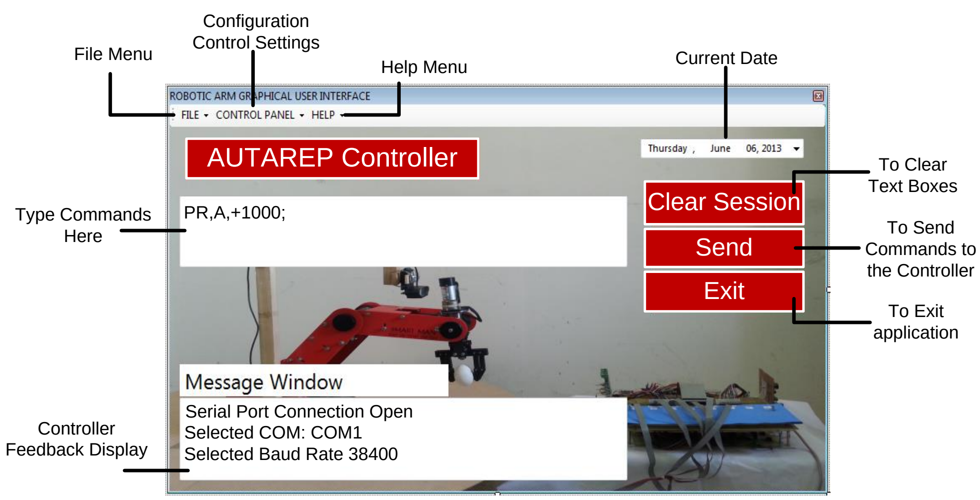


Figure 7. AUTAREP GUI [36]

REAL TRAINING PLATFORMS

Despite offering several advantages, simulation-based training paradigms suffer from various serious constraints. Their limitations often lead to insufficient exposure of practicality in contrast to the performance of a real framework. This may happen because of their existence in a totally 'virtual' environment. Regarding precision, reliability and repeatability, the results of experiments which are obtained by using a virtual tool may not be compared with the same trials that are conducted on a real robot. This is primarily because of the practical limitations of actuators and sensors, and various other non-linearities of the real-world mechatronic systems [25]. Moreover, virtual platforms may make the actual understanding of the underlying concept cumbersome because of inadequate mapping to the reality. In contrast, training platforms employing a real robotic arm significantly help trainers to bridge the gap between theory and practice effectively so as to maintain trainees' interest throughout the instructional sessions. A survey has shown that incorporating real robots in conventional robot teaching methods helps to enhance students' skills and competence to solve problems in the realistic context [80]. So an effective learning environment in a robotics laboratory or research-oriented industry cannot be created without training students and internees on a real robotic arm.

Most of the existing cheap platforms are manufactured from polyvinyl chloride or aluminium with actuation based on DC servo motors. General purpose robot training platforms like LEGO blocks can also find potential for constructing a small prototype of multi-configuration robots for educational and experimental purposes. Specific frameworks reported in the scientific community for teaching and training in 5-7-DOF arms are mentioned below.

5-DOF Arm

With five DOF or more, the robot can be used for advanced applications such as grasping and moving around with a minimum number of moves. OWI-535 is a simple but affordable platform for novices [81]. Built with plastic, the robot has 4 DOF for the arm and 1 DOF for the gripper. It can be controlled with either a five-switch wired controller or a computer by using additional electronics. Lynxmotion has developed and marketed three robotic arms: AL5A, AL5B and AL5D [82]. Mover 4 is another training platform having four servo joints [83].

6-DOF Arm

With only one DOF less than the human arm, a robotic arm with 6 DOF can be used in complex applications where an object can be moved up and down, left and right, or forward and backward. Most of the reported educational platforms have 6 DOF. Crust Crawler Inc. has presented several open-source educational robotic platforms with state-of-the-art functionality [84]. These include AX-12A, AX-18A, SG5 and SG6. It is claimed by the manufacturer that the AX-18A is the only robotic arm available in the market that features diverse feedback including position, voltage, current and temperature. SCORBOT-ER 4u is another training platform which is actuated with servos and equipped with a high-resolution incremental optical encoder on each axis and gripper [85]. The torque/force is transmitted through gears, timing belts and lead screw.

Rhino Robotics Ltd. offer a comprehensive line of rugged, semi-enclosed designed robots including XR-3, XR-4 and SCARA [86]. The differences between XR-3 and XR-4 are in their mechanical design, read-only memory and payload capacity. Both are actuated with six permanent-magnet DC servo motors having integral gearboxes and equipped with incremental optical encoders. The robots can be controlled using a teaching pendant or through software 'RobotTalk.' ED-7220C is another platform whose mechatronic design is very similar to SCORBOT-ER 4u, while its controller is exactly the same as the XR-4 [87].

7-DOF Arm

Seven DOF indicate that the robotic arm can compete with a human arm. At this point a user can build robotic applications which can entirely replace the human workers, as witnessed by the DLR-KUKA success story [88]. Claimed by the company that the arm from KUKA is the "fastest robot on earth", it is among the most reliable robots in their class. The light-weight robot assists

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engineers and researchers in developing innovative industrial applications because of its low-mass payload ratio and active programmable compliance. The co-ordinated link (COOL) arm 7D300 is another 7-DOF platform which has been presented by Asimov Robotics [89]. The specifications of hardware platforms which are designed for teaching and training purposes are presented in Table 3.

Table 3. Comparative review of real robotic platforms

Platform	Manufacturer	Payload [kg]	Weight [kg]	Reach [mm]	Price [$]
5 DOF					
535	OWI Robots	0.1	0.658	320.04	29.99
AL5D	Lynxmotion	0.37	1.6	250	359.76
xMover 4	Commonplace Rob.	0.5	3.5	550	3948.00
6 DOF					
AS-6 DOF	Robot Base		1.03	324	280.00
CS–113	Weartronics	0.5	8.0	445	2500.00
AX-18A Series	Crust Crawler	0.907	0.906	539.7	399.00 –1195.00
SCORBOT-ER 4u	Intelitek Robotics	2.1	10.8	610	8300.43
XR-4	Rhino	2.0	15.9	609.6	21113.00
7220C	ED Corporation	1.0	33.0	610	8039.00
IT-Robot	TeraSoft	0.1	2.0	410	3100.00
JACO	Kinova	1.5	5.0	900	48403.00
5250	Lab Volt	4.5	21.6	431.8	35000
VS087	Denso	7.0	51.0	905	26017
7 DOF					
KUKA	LWR4+	7.0	16.0	790	Not available
COOL Arm 7D300	Asimov Robotics	0.3	1.35	50	Not available

Another relevant concept worth mentioning here is the e-laboratory-based platform. This platform integrates several remote and virtual control elements and learning modules to benefit students by providing hands-on experience in a remotely-located real robotic manipulator. A pilot study conducted by Tzafestas et al. [90] using a 4-DOF adept One-MV robot demonstrates the potential of e-laboratory. The study presents a comparative evaluation of three modalities: real, remote and virtual training in the programming of pick-and-place task. A t-test of these independent modalities was performed to determine if significant differences exist among the mean scores based on committed errors related to low-level technical skills, mid/high-level skills, time and total. The evaluation results are shown in Figure 8.

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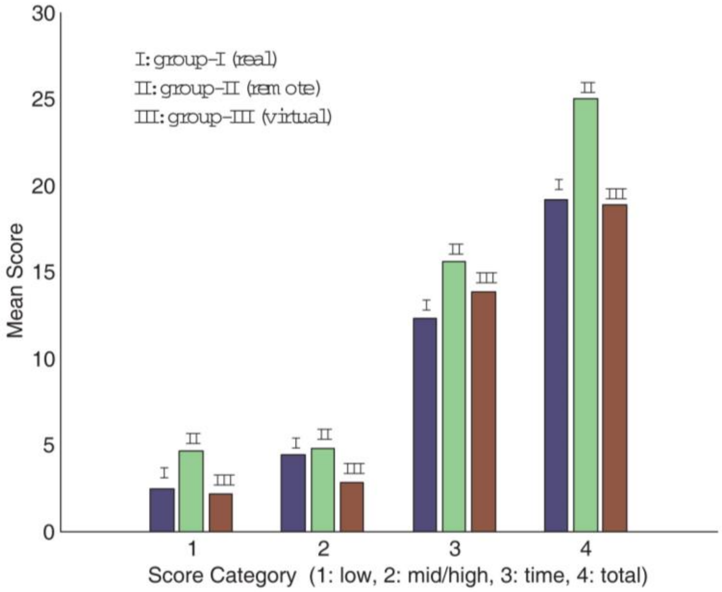

Figure 8. Mean scores of the three modalities in final assessment test [90]

CONCLUSIONS

This research study presents a comprehensive review of educational robotic frameworks, which may help in to the selection of appropriate virtual/real training platforms corresponding to specific requirements and budget limitations. It may also serve as a worthy source of information for the researchers who are developing the training platforms on robotics.

It is envisaged that in the near future robotic frameworks will have more diversified capabilities. Going beyond trivial control strategies, virtual robotic simulators will be able to apply non-linear, robust and intelligent control laws. The upcoming 'soft' robotic platforms will be closer to the actual robots and will also be able to simulate the performance of the user's newly-created designs in terms of stability, reliability, repeatability, precision, structural analysis, etc. Also, the integration of VR and CAD needs to be further strengthened. With recent cost-effective advancements in mechatronics and computing, it is hoped that in the near future the research community will see much cheaper robots that still provide adequate sensing and actuation capabilities for use as pseudo-industrial manipulators in the laboratories.

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