Synovision
Solutions LLC
6237 Garretson Street, Burke, VA 22015 Phone: (703) 286-7214

Common Robot Controller Study

Final Report

FY 2007

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Executive Summary

This study was performed by Synovision Solutions LLC under the auspices of the Department of Defense (DoD) Joint Ground Robotics Enterprise (JGRE). The purpose of this study was to survey ongoing robotic controller efforts and to distill from the survey appropriate guidance to the DoD on how to best acquire a common robotic controller. The study was not intended to actually build such a controller, but rather to assess the state of the art of universal robot controllers, identify duplication of efforts and redundancies if any, and develop a value framework for a feasible path forward for a common controller effort. Additional JGRE guidance cautioned that the budget climate across all DoD programs was expected to be austere and funding reductions in these programs could be severely reduced including the Future Combat Systems. The study recognized that robotic controller efforts are ongoing across all DoD components and there should be no bias towards any one service. The study found that there are at least two DoD initiatives that are making good progress towards the goal of a common controller and that they, like the services' research laboratories, are not unproductive redundancies. It also found that there are a number of private enterprise robotic efforts which, although their work is proprietary, are willing to share findings and in some cases move to an open (public) architecture to aid the pursuit of a common robotic controller. These private enterprise efforts were not redundant, but were small, niche applications and are currently not moving towards the goal of a common controller. This study, although somewhat limited in scope and duration, convened a two-day workshop of willing commercial entities which shared their views of a common controller roadmap. Some invited enterprises did not or could not attend the workshop. Those that did gave useful insights. Their subject matter expertise enabled certain conclusions in this study which recommends an incremental, evolutionary bottom-up architectural migration path towards the goal of a common robotic controller. The study further recommends the establishment of a small body of experts to develop a common controller architecture. This recommendation is based on the synergistic effect of both what is realizable in the normal technological migration towards standards, ongoing standardization efforts by certain standing organizations and committees, and the expected insertion of artificial intelligence advancements in the robots themselves making them more autonomous, thus less reliant on human controller activities. It is the conjunction of emerging standards and technological advancements which give the realization of a common controller a distinct possibility and a vector to pursue.

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1. Introduction:

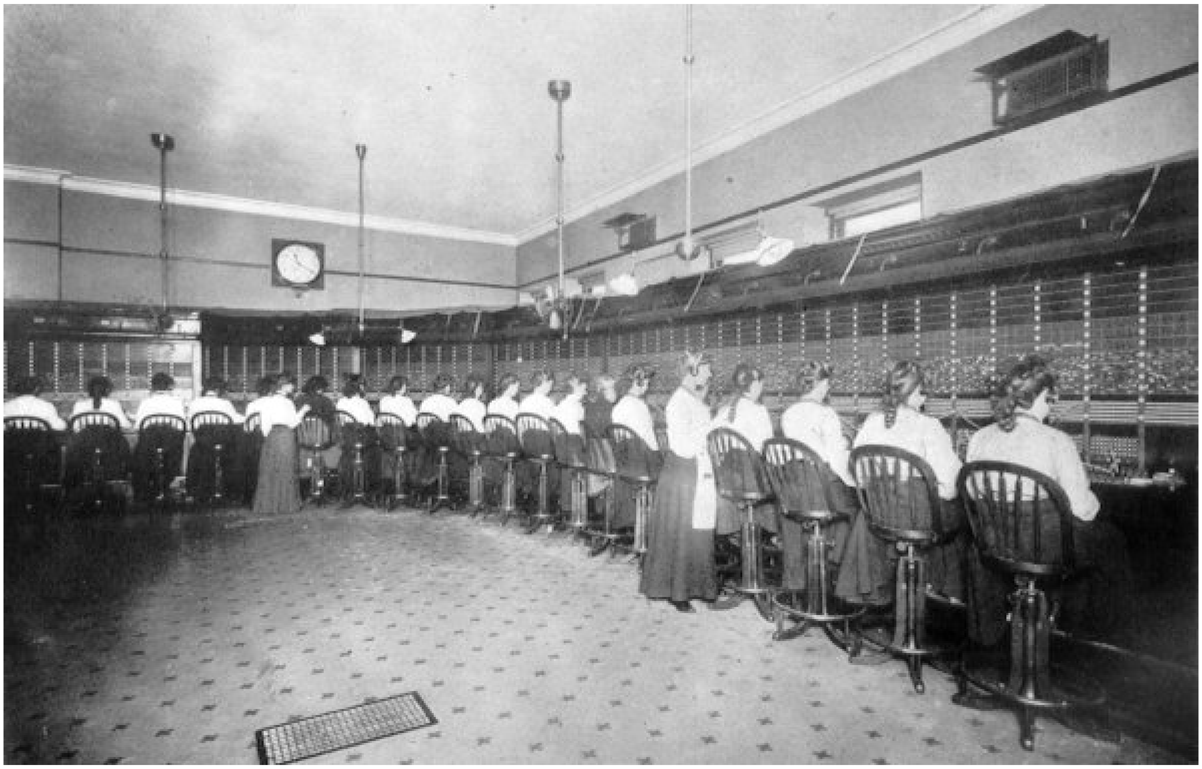
It should be clear to all concerned in the pursuit of a common robotic controller that they share in the multitude and variety of such pursuits across all domains and all enterprises that wish to attain commonality for specific reasons. Usually these reasons stem from attaining greater market share in commercial products, efficiencies in manufacturing, reduced cost per unit of production, and establishing de facto, national, and international standards. Standardization across any enterprise provides the *lingua franca* for the growth, training, equipping, repairing, and acceptance of products necessary for the building and sustainment of an enterprise. What emerges in the initial start of any enterprise is the number of disparate instances which initially share few if any common aspects of design, interfaces, or sharing of specifications. That is, they do not share an architectural framework or standard reference. This is natural and expected since most of all human endeavor is “bottom-up” from an architectural viewpoint. A top-down driven architecture requires near omniscience of everything that is to come in the future with respect to an enterprise and this simply has never been the case for virtually everything that has ever been invented. The automotive and the electronics industries are but two examples of enterprises that have grown to adopt standards over time after an initial disjointed appearance of products and services – they are the Society of Automotive Engineers (SAE) and the Institute for Electrical and Electronic Engineers (IEEE) respectively.

The military use of robotics is no exception to the above historical perspective. A dozen years ago, the use of robotics on the battlefield did not enjoy the same acceptance that it enjoys today. There were fears of machines gone awry and resistance to pilotless aircraft. These fears predated what military transformation was about to incorporate. Transformation, over the last eight years, has created a vision of not only how we will fight in the future, but also what equipment we will fight with which now includes pilotless airplanes and robots. The early fears of the “horseless carriage” from a century ago fit the same apprehension about robots. But after the gradual utility, economy, and leverage that robots have demonstrated in the last four years that Operation Iraqi Freedom (OIF) and Operation Enduring Freedom (OEF) have demonstrated, not only has the acceptance of battlefield robotics increased, but also the sheer number of robots has exploded in variety and type across all services. In addition, the stage of military robotics has moved from advocacy by futurists to law by legislators. Indeed, the use robots is mandated by Public Law 106-398 which has set a goal of one third of ground combat vehicles will be unmanned by 2015.

Such mandates and its concomitant Congressional oversight provide the driving function to move towards standards and their expected efficiencies. But the horse in some sense is already out of the barn and there already exist a successful variety of unmanned aerial, ground, and underwater vehicles performing a multitude of functions across a variety of domains. The drawing board for such vehicles is already replete with new families and applications for robots and it would appear that there are no standards yet applied to this fast growing enterprise. To be sure, there are already sets of standards which of necessity are being applied at the technical level of component assemblies. In fact, SAE, IEEE, National Institute of Standards (NIST), and military standards (MIL-STD) are already applied to military robotics. For example, MIL-STD 1760 provides a common electrical and digital interface between weapons and aircraft. The standard MIL-STD-1760 connecter is used to transfer guidance information to weapons and makes it easier (cheaper) to add weapons in the future. Standard NATO Agreements (STANAGs) are also already applied to military unattended aerial vehicles (UAVs) such as STANAG 4586 which allows NATO member nations to jointly support military operations using their own UAVs and ground control station equipment. This increases interoperability and allows data and information to be processed by member nation UAVs to share in real-time through a common ground interface. Thus, there is early evidence that a bottom-up movement towards a common robotic architecture is in progress and sharing success.

The development of common robotic controllers, however, is less evident. As the number of robots has increased in type, so has the number of controllers for each type robot. The state of the art for most robots is primarily teleoperated which means that each step or motion of a robot is guided in real-time by an operator who transmits, usually by radio, individual commands for each movement of the robot. This one-to-one relationship does not scale to the one-to-many vision of an operator controlling multiple robots of the same type and, further, swarms of robots of a variety of types. There is no known architecture framework which encapsulates this vision of the future, and consequently, there is little or no movement towards a common robot controller that would embody such functionality.

In addition for the need to adopt a controller architecture framework, there is also the need to move from the present military application of robots to the military mission and purpose of robotics on the battlefield. This conceptual leap to the future employment of robots requires a similar leap beyond the teleoperated robots of today. That is, teleoperation of robots does not scale to their future employment and roles for mission accomplishment. Fifty years after the invention of the telephone it was feared that, because of the exponential growth of calls being made, nearly one out of two persons would have to be a telephone operator.



Picture (above) of a 1910 telephone exchange in New York City taken from Casson, H. N., *The History of the Telephone.* Chicago: A. C. McClurg & Co., 1910.

Picture at right. In what seems to be a game of one-up-manship, University of Pennsylvania researchers have announced that they have received a $5 million grant to develop large-scale robot swarms that would coordinate activities between the ground and sky. The robot swarm would act autonomously sharing data to coordinate action and survey their environment. The new system would draw on knowledge of biological signaling and cooperation. The scale of the proposed swarms is described as "immense." Taken from robotsnext.blogspot.com/2005_05_01_robotsnext_archive.htm.

Manual (teleoperated) switchboards were replaced with electromechanical switching systems which eliminated this doomsday scenario. Similarly, the vision for multiple, clustered, swarming, and group cooperative robotic systems on the battlefield would require nearly every other soldier to be a robot operator and clearly this cannot be the expectation. Consequently, there is a need for robot controllers which incorporates future robots (clustered, swarmed, and cooperating groups) in a manner which is complementary to the way soldiers fight toward the goal of mission accomplishment and purpose. The convergence of these needed controllers will not spontaneously erupt. They must be deliberate and adhere to an architecture which incrementally incorporates the evolution of robot military applications and the way in which the future force will “command and control” the new robotic augmentation to the unit.

The next section will provide a methodology for a common robot controller architecture. Generically, an architecture consists of three perspective views – the operational, system, and technical views. A common robot controller for the robots in the air, on the ground, and under the sea will require the rigor of incorporating all three perspective views in order to graduate from the disjointed control of teleoperated robots of today to the command and control of near-autonomous clusters and swarms of robots for the future force. To be compatible for soldier operators of that future force, the human factors with regard the operational architectural view of robotic controllers will be distinct from either the system view or the technical view of such an architecture. The operational architecture view must truly encompass the notion of a fighting partner of the unit. The partner will have a degree of autonomy and even artificial intelligence in order for human soldiers to not only command robots but also rely on their mission accomplishment. The need for terminating or aborting the mission will be retained by the "man-in-the-loop."

2. Methodological Model of the Problem Space

The DoD, after recognizing the explosion of the number of system architectures that were appearing throughout the enterprise, undertook the creation of the DoD Architecture Framework (DoDAF). It was published as the DoDAF Version 1.0 Deskbook, 9 February 2004. The IEEE defines the term architecture as the “structure of components, their relationships, and the principles and guidelines governing their design and evolution over time.” The Framework is careful to differentiate between an architecture description and an architecture implementation. The description means the “blueprint,” while the implementation means the real-world capabilities and assets in the field. The Framework does not address how the blueprint-to-implementation process takes place. The Framework does, however, divide an architecture into three views – the operational, systems, and technical views which are defined as follows:

- Operational Architecture View: a description of the tasks and activities, operational elements, and information flows required to accomplish or support a military operation.

- System Architecture View: a description, including graphics, of systems and interconnections providing for, or supporting, warfighting functions.

- Technical Architecture View: the minimal set of rules governing the arrangement, interaction, and interdependence of system parts or elements, whose purpose is to ensure that a conformant system satisfies a specified set of requirements.

To be sure, a common robotic controller is going to embody all three of the architectural views established by the Framework. But it should be emphasized that it is the operational view which sets this component (the controller) apart from the robot itself because it establishes the man-machine interface concepts that are totally unique from, for example, the electrical connection bus or a propulsion system for the robot.

This study established that a variety of approaches towards robot controllers are underway which examine how and how well humans interact with a controller to perform the robotic function tasks at hand. The examination of these controllers was limited to the input surveyed from the providers found in Appendix A, but what is useful to note in general is that the human factor in robotic controllers is soldier specific and more qualitative than quantitative in nature. That is to say, that the number of buttons, the array of such buttons, and the “intuition” among soldiers that tested robotic controllers was not a universal “yes” or “no” vote. Rather, the variety of responses to the controllers tested gave some indication to preference, although this could be expected to change with sample size and future experiences with robotics.

The study also found that the ability of soldiers to maneuver robots with controllers was a time consuming task that required considerable direct attention to the task at hand. It also found that the centralization of controlling multiple robots by a given controller/soldier became exponentially more difficult with the current controller technology. From this perspective, the study steps back from the micro-examination of ongoing common controller efforts to see the “forest for the trees” with regard to the control of robots on the battlefield.

Robots on the battlefield (in the limit) could be envisioned to be fully autonomous, that is, in the limit, there would be no need for a controller per se. An intriguing paper stated that “an ultimate goal would be to eliminate the need for a robot controller altogether [Everett, SPIE Proc. 5609]. Rather, a high-level command or directive would be conveyed to the robot (perhaps by voice) with an expectation of mission execution and success, just as with any other member of a trained unit. To some extent, a class of UAVs already achieves this expectation. The JDAM munition, incorporating GPS navigation, has an expected and acceptable error circle probable which requires no human control after the command to launch. Stepping down one notch from this concept are the latest Mars rover robots which must incorporate some level of “intelligence” to make moves decoupled from direct and immediate human interface. This is primarily driven by the limitations imposed by the speed of light which demands a minimum of anywhere between 10 and 22 minutes of earth-based controller delay because of the relative orbital distances between Earth and Mars. Consequently, teleoperation in real-time is not possible with Mars rovers, so a degree of autonomy is essential. Thus, on board intelligence (artificial intelligence or AI) is a measure of autonomy that is accepted by the human controller within the boundary conditions of mission success or failure. So for example, the Martian rover might be permitted to drive several hundred feet between Earth-based inspection and correction before it proceeds lest it falls into a crater. Similarly, a ground combat robotic mule could be given waypoints to achieve, but pause occasionally to be controlled for fear of driving into a lake.

Lastly, stepping down still further in robotic maturation, are the completely teleoperated robots that are tethered in real-time to the operator for each maneuver and function. Thus there are hierarchies of robots, already in existence, that display functionality across the spectrum of autonomy. As onboard sensors, terrain data, and decision systems improve, the onboard intelligence of the robots should also improve. As they become incrementally more intelligent, they take a step closer to autonomy. How parents allow children to depart home for longer periods as they age comes to mind here. Each incremental step forward in AI would need an incremental step forward in the hierarchy of operational views of a controller architecture. Indeed, the challenge is formidable and there is research underway at such organizations as the Office of Naval Research, NASA, NIST, MIT, and the Carnegie-Mellon Field Robotics Center (CMFRC). The latter has a proposal which states the following:

> “The main technical challenge of the project is to develop an architectural framework that permits a high degree of autonomy for each individual robot, while providing a coordination structure that enables the group to act as a unified team.”

There is also evidence that the full spectrum of robotic architectures will require multiple architectures at each incremental step from one end of this spectrum. When queried about such a notion, the CMFRC replies, “for example, an architecture well suited for direct teleoperation tends not to be amenable for supervisory control or for autonomous use” [Dowling].

This study envisions the ability of human robotic operators to interface with their robots with dramatic increase in scope and number. The study recognizes that, in the limit, what a operator would most desire is to give a high-level command to the robot as it might give an order to a soldier to maneuver to an objective, identify and eliminate threats, or simply “follow me.” This might be the case with a load bearing mule without the need for a controller of any sort, notwithstanding the ability to override the command with an “abort” or “recover” command. In this way, and perhaps only in this way, could an operator be expected to be in “command” of a robotic ground platoon or air squadron which exhibit independent actions by multiple players across a variety of functions as one might expect command over human organizations of which similar missions are entrusted.

Two curves that represent the objective common controller and the relationship with the current situation as represented in the figure below.

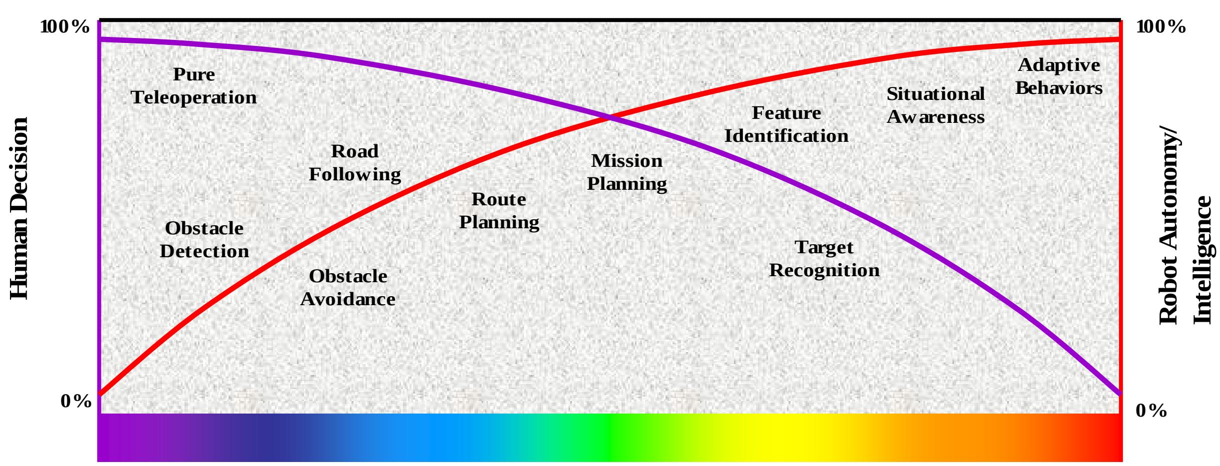


Figure from JAUGS Online Tutorial

What this figure indicates is that, as robot autonomy/intelligence increases, the need for human decision making decreases. This is a generalized approach and conceptual model. What the model lacks is a time scale over which one could predict when these relationships are realizable. On the other hand, there are many indicators which should instill some measure of confidence that it in fact will be realizable. The predictions given by Moore's Law, the measurable and exponential rise of computational power, the relative decrease in size and power of future machines (both mechanical and computer), the promise of nanotechnology, and even the concept of the "singularity" when the so-called Touring Test may claim a winner, all give rise to the eventual elimination of robotic controllers almost completely. The above figure represents the full spectrum from teleoperation to full autonomy and intelligence with incremental way points along the way. Some of these way points are obstacle detection, obstacle avoidance, road following, road planning, mission planning, feature identification, situational awareness, and adaptive behaviors. Each successive step across this spectrum is incrementally more complex than the next. Each will require its own architecture. But, with vision, leadership, and funding/influence, each architecture should build on its predecessor if the framework is sound. The JGRE has a unique role and responsibility to build an Architecture Framework for military robotics and their associated controllers.

Thus in the determination of whether the pursuit of a common robotic controller is needed and the corresponding level of effort that might be necessary to implement such a necessity, there needs to be some incorporation of an assessment of what might occur as a natural evolution over time as machines acquire more intelligence and thus more autonomy. This study will not make such an assessment, but it is possible to conclude that a simple "do nothing" approach to achieving a common controller (read autonomous robot) is not inconceivable and might best be considered by such a body as the Defense Science Board. That is to say, there is a finite possibility that the robotics industry will gravitate over time to a family of controllers that will satisfy the requirement of commonality. How quickly this would occur is at issue, and prejudging the answer would indicate that it would take too long. So a more pragmatic approach might be to influence the convergence of multiple controllers across families of robots such as to hasten this convergence in some incremental fashion which gives impetus and commonality to the effort. This study will conclude with recommendations for the latter.

To develop the recommendations for this study, a two-day panel of industry experts was assembled. The next section will summarize the data which was surveyed by the panel of industry representatives, conducted in April 2007, which established a status quo baseline of robotic controller efforts to date.

3. Panel Review Report

Background: Synovision Solutions conducted a panel session in order to compile the appropriate characteristics of controller systems for military robotics for the Department of Defense Joint Ground Robotics Enterprise. The panel evaluated twelve current programs and providers for controller systems. The panel met for two days in the Washington, DC metro area and focused on the status of current requirements and directions of the providers. On the first day, the panel concentrated on reviewing a sampling of ongoing robotic programs. On the second day, the committee distilled and refined the set of attributes needed and the technical approaches taken to date for developing a universal robotic controller. Recommendations for action by the Joint Ground Robotics Enterprise office were encapsulated.

The panel consisted of the following personnel:

- Dr. Bruce Jette (Army Science Board Member and Synovision Solutions President), Panel Chairman
- Dr. Joe Braddock (Army Science Board Member and former Co-Founder of BDM Corporation)
- Dr. Petras "Pepi" Avizonis (Trexenterprises)
- Mr. Kevin Cogan, Colonel, U.S. Army (ret.) (US Army War College Adjunct Faculty Member)
- Mr. Peter Wells (Foster-Miller)
- Mr. Tom Frost (iRobot)
- Mr. Edison Hudson (iRobot, Deputy Director of Research)
- Mr. Mark Gillespie (Synovision Solutions Director of Studies) served as the Study Director

Day One

The panel's deliberations began with a discussion of the reasons behind the need for the study by the JGRE's director. In short, there was a need for the panel to review the current projects, identify any programs (or parts thereof) that gave the appearance of overlapping, evaluate whether these were true redundancies and, if so, make appropriate recommendations to eliminate unproductive redundancies as well as provide appropriate justification for any positive aspects of overlapping projects (if the panel found any that were positive). The resulting recommendations should provide a coherent "story" to both internal and external audiences. It was recognized that this was a challenging mission in a space not well defined, but one that ultimately would benefit the warfighting soldiers, sailors, airmen, and marines of the future force. Part of the challenge is to provide a robust study without the appearance of any particular service bias. The outcome should be a foundational document to help provide DoD guidance on how to go about acquiring the best common robotic controller and not an exercise in how to actually build a common controller. In particular, it was noted that funding across all DoD programs is expected to get extremely tight and that all programs were vulnerable to severe reduction in funding, even Future Combat Systems.

The panel reviewed of the following projects in succession (see Appendix A for more detailed information regarding each project):

1. The Future Combat System's Common Controller
2. SPAWAR Systems Center's Multi-Robot Operator Control Unit (MOCU)
3. Night Vision Electronic Sensors Division's Wearable OCU;
4. Applied Perception, Incorporated's Soldier Universal Robot Controller (SURC)
5. AnthroTronix, Incorporated's Wrist Mounted Operator Control Unit (MOCU)
6. Chatten Associate's Dismounted Controller Device
7. General Dynamics' THOR system
8. Aviation Missile Research, Development and Engineering Center's Dismounted Common Handheld Controller
9. Nomadio's GC-205 Control System
10. Navy Sea Systems Command's JUSC2
11. Marine Corps Warfighting Lab's Modular Wearable Computer (MOWC)
12. QinetiQ's Appliqué Robotics Kit Controller

Below, in bullet form, are the salient observations made by the panel as it reviewed the twelve systems which were voluntarily submitted by the government or industry. Some invitees did not respond to the data call. Consequently, the observations can only be considered a sampling of ongoing robot controller efforts and is necessarily incomplete. But it is deemed sufficiently broad to draw conclusions for the way ahead in the last two sections of this report.

- The MOCU system seemed more architecture than product
- Radios on the controller systems need to be modular and easily removable at the operator level
- The type of communications system (Ethernet or serial radio) is yet to be determined
- The issue of signals interference between UAVs and UGVs was touched on as one in need of immediate attention
- The capability for robots to follow lights (such as illuminating a target with laser light or infrared) should be examined
- An attribute of a control architecture should be to handle "route replanning" (the ability through artificial intelligence to autonomously adjust back to an original way or path)
- An attribute should be for the common controller to detect and alert the operator when another controller is trying to take control of one of its robots

- FCS' behavior pattern thus far is overly methodical and suggests that it is not taking recent developments by other programs into consideration that very likely will shorten FCS' own development cycle; the preference seems to be that they will develop everything themselves anyway
- There seems to be some overlap between MOCU and SURC: A request for all 54 requirements listed in the SURC briefing should be made; SURC, however seems to be focused on "visual software processing for imaging" and "data processing for imaging;" SURC also concentrates on maps, visualization and maneuver
- There seems to be some overlap between JUSC2 with FCS and to some extent MOCU
- GDRS' THOR appears to be overlapping greatly with FCS', JUSC2's and SPAWARS' programs
- Robots and controllers should be IP addressable

Day Two

Dr. Joe Braddock joined the panel discussions on Day 2. Observations from all of the panel on Day 2 are as follows:

- The attributes of a universal controller should conform to a set of well defined meanings; however, it should be in the lexicon of the warfighter where the controllers are designed to be used
- Additionally, attention should be paid to make the controlling interface act more in line with how warfighters actually fight (in essence, less like a technician sitting behind a computer console) [Braddock]
- Further adding to the above, attention should also be given to controllers that have the robots motion mimic the actual physical motion imparted to the OCU's control devices; in essence, move toward control systems like the Nintendo Wii or AnthroTronix's instrumented glove (iGlove) in contrast to the PlayStation 2
- The overly deliberate pace of FCS is apparent in their wanting to start at the very beginning of the development cycle despite the other R&D programs in existence (e.g., SPAWARS , JUSC2 and a host of smaller projects) whose work could be leveraged to move them much faster
- Adding to FCS' problem is the fact that contractors executing the R&D have no incentive to move the development any faster (e.g., they will "milk" spiral 1, then go on to milk spiral 2, etc.)
- A definitional challenge that needs to be addressed is the issue of UAVs that may land on the ground and then perform an activity (either as a stationary sensor or, more complicated, begin moving on terrain as does a UGV)
- An attribute of a universal robot controller should be to allow for multiple controllers to be linked to the robot in a hierarchical control matrix to allow for instances when the primary operator is incapacitated on the battlefield or the communications link is broken with the primary operator for whatever reason

- One suggestion was to add a capability for a robot to remotely dispense signal re-transmitters along its route to ensure adequate communications links in areas where terrain or distance could be an issue… (recognizing, however, this is not an attribute of the common controller)
- The mixture of UAVs and UGVs to provide 3-Dimensional action and capability gives such a significant advantage to warfighters that perhaps even a 20% solution is worthy of fielding
- Robotics usage and training is nowhere to be found in the Army's current training programs
- Scaling issues need to be addressed such as how many robots should a universal robotic controller need to be able to control at one time?
- The systems engineering method used by FCS's contractor (Boeing) is reflective of the aircraft industry which may be fine for an aircraft but is too unwieldy and perhaps unnecessarily slow for developing a ground robot universal controller system
- A programmatic approach of successively iterating the sequence of rapid building, fielding, receiving feedback from the field and then incorporating the feedback is preferred (a build a little, test a little or "It is more an journey than a goal" approach)
- The approach should emphasize making robots effective in an operational environment
- An attribute that deserves great attention is the authentication/safety issue for robots that have been weaponized
- **There is no standard systems architecture for robotic systems (emphasis added)**
- Three observations…the enemy always gets a vote, the operator can only contribute valuable feedback <u>after</u> the equipment is fielded, and there is no robotic commercial sector "throwing things over the wall"
- The whole robotics development cycle strategy should be one of an <u>evolutionary</u> basis in which it is accepted from the beginning that every 5 years one simply throws out the old equipment/technology and procures that with the latest advances [Moore's Law assures obsolescence in 5 years or sooner]
- Requiring the JTRS radios to be on every robot makes the cost prohibitive…this needs rethinking for potentially very expendable robot [milspec requirements should be resisted in situations where it drives costs to impracticality]
- JTRS defining the pipes through which controller signals must pass is a problem for future common controller architectures
- There is a need to have a DoD robotics technology repository that will make DoD's robotics research/knowledge available to all other DoD R&D efforts in robotics
- A commercial panel member suggested that if COTS is to be provided in the controller systems, it must be written in XML
- There is concern that the emphasis on common controllers is too focused on equipping FCS and not the bulk of the future force

- Use a Battle Command Program Migration model for the universal robot controller [see next section]

Panel Session Conclusions/Way Forward

- FCS Common Controller and JUSC2 could benefit from collaboration
  - More than half of their platforms overlap
  - Appear to have very similar goals
  - Drawback may be ‘too many cooks’ adding requirements…
- THOR should go away since it is truly redundant with FCS CC and JUSC2
- Small programs should ‘feed’ FCS/JUSC2
- FCS/JUSC2 should perform detailed lessons learned from previous and existing systems (Land Warrior, M7, TM7, ARC, as well as the current state of controllers and how things are done)
  - Why was Land Warrior cancelled
  - What is good/bad about M7, ARC, etc.
  - Why are the current controllers configured in the way they are? EOD personnel actually like the Talon suit-case controller…
  - Apply those lessons to current development
  - Do not reinvent wheels
  - Do not repeat previous failures
- Some technologies may not currently be pushed hard enough. For example, autonomy to ‘run with me.’ Current platforms are primarily pure teleoperation.
  - Review current autonomy efforts, since the level of autonomy will have huge impact on controller (for example – replace joysticks with voice-control)

Timeline and Shortcomings

- FCS
  - First usable/testable system scheduled for 2012
  - Only provides answer for small fragment of the Army
  - Relies on non-existent and potentially very expensive radio

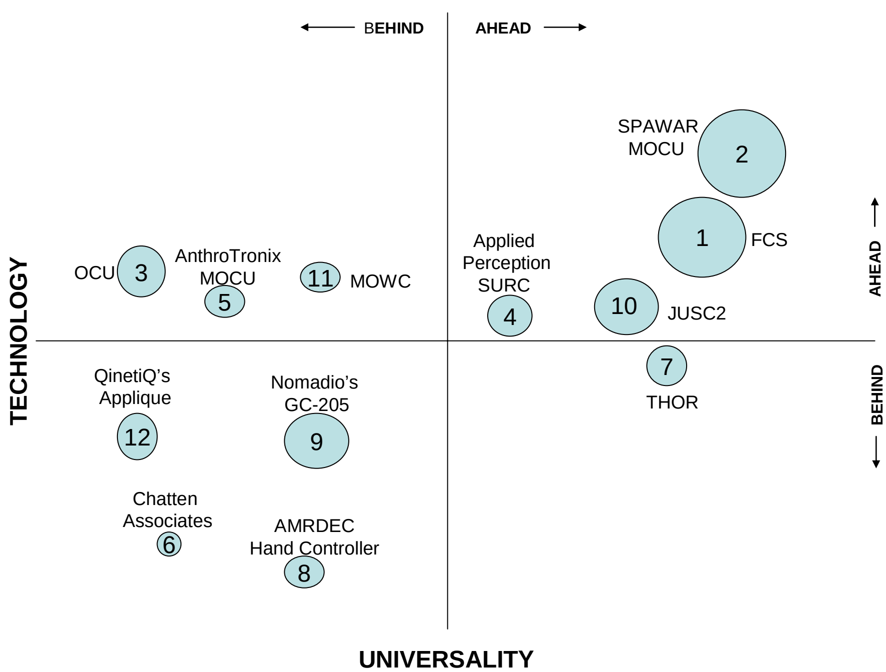
- RSJPO/Indian Head
  - Providing current class of platforms to theater (Talon, PackBot, MarkBot, BomBot, etc.)
  - Not providing holistic solutions, only point-solutions

- What is being done for the non-FCS Army
- What is planned for the next 5 years
  - FCS is supposed to ‘spin-out’ interim solutions, but this clearly can not happen if their first ‘solution’ is not due until 2012!

Design Philosophies

- Boeing FCS is applying same process to every component of the program
  - Design of 747 requires tedious and detailed process – this is good
  - Same process is being applied to UGVs and soldier systems – this is bad
  - Apply 747 process to controller, you will likely wind up with a controller that looks like a 747
- Smaller systems (UGVs, Controllers, Soldier Systems) do not require the same process
  - 747 can not use a “build it and try it out” approach – it is likely to fall out of the sky if it is done wrong
  - Build, Try, Fix approach may work better and provide more immediate results (address interim problems). Errors in rapid build/try will not result in catastrophic results
  - Smaller systems are not expected to have same life-cycles as larger systems, therefore should not go through the same process (at least the same timescale)

Given the many issues discussed in somewhat of a random assessment of all twelve systems surveyed, the complexity of a side-by-side is best portrayed in the form of “quad chart” which depicts Technology versus Universality on the axes. The size of the circle depicts a notion of scope of the program, but in no way should it be interpreted as being to scale, since no quantitative data was available to the panel.



Comparison of efforts (Technology vs. Universality), keyed to Appendix A

4. Future Direction

In the previous section, the panel observed the expected delay in the Future Combat Systems (FCS) program. Additionally, the specific robotic platforms envisioned for FCS are far from a complete suite of robotics envisioned for the future, both before and after FCS fielding. Consequently, this study concludes that the FCS program is not and cannot be the boilerplate for the robotic controller architecture of the future, despite its current scope and prominence. Further, it concludes that the FCS program, albeit valuable insights on robotics might spinout, will remain a fairly closed system with little opportunity to influence its direction towards a common controller from outside agencies. Consequently, the way ahead must leverage robotic efforts outside of the FCS program, but that is not deemed to be a limiting factor nor a detriment to the goal of a common controller. As noted in the previous section, the panel assessed FCS as having a narrow view of what is needed to that end.

As indicated in the opening of this report, the issue of commonality is not unique to robotics and its requisite controllers. At least since the dawn of mechanical systems and the industrial age, manufacturing standards, interchangeable parts, and interoperability have been lofty goals. In fact, these goals have been attained in a large number of industries and the emergence of like-minded societies to govern commonality issues. To date, the luxury of a “Society of Common Operational Robot Engineers (SCORE)” does not exist, but a prototype does as embodied in the Joint Architecture for Unmanned Systems (JAUS). The JGRE is well-versed in JAUS and there is no need for this study to elaborate on it here, other to emphasize that it professes to comply with the Joint Technical Architecture and the SAE Generic Open Architecture. JAUS is committed to remain flexible to accommodate technology advancements. Because JAUS is sanctioned by the JGRE with the goals of reducing life cycle costs, reducing development and integration time, providing a framework for technology insertion, and accommodating the expansion of existing systems with new capabilities, it has the underpinnings for an excellent standardization effort for the future of robotics in general. A member of this study has attended a recent JAUS workshop. It would be an easy recommendation to simply assign the task of a common controller architecture to JAUS as a new subcommittee effort, and that is a future possibility. However, a number of encumbrances would arise if this was the immediate course of action, which is not recommended.

Short of such a recommendation for JAUS, the study will recommend a full-time independent committee of two to three people and the remainder of the committee from the robotics community, both government and industry. From all of the assessment in the preceding section and the early discussion of “bottom-up” evolution to a common standard, what is principally lacking in the robotics controller arena is any top-down view of a controller architecture and a policy which would drive a common controller architecture as what is required for robotics in general as in JAUS. A stepwise, evolvable migration path from present teleoperated robotic platforms to the eventual end-state of autonomous/AI directed teams, clusters, and swarms of robots has neither a top-down architectural view, nor an investment strategy to get there. Simply put, there is no policy and investment strategy to establish a common controller effort and this would seem to be the overarching criticism of any such semblance of a common controller today. This point is primary, and it really is set apart from the comparison of ongoing programs, such as the dozen assessed by the panel here. The dozen represent the result of virtually no policy or top-down architectural view. It is truly not their fault, nor really their problem, since military robotics requirements to this point have merely been leveraged to solve operational domain (not mission) short-term problems, in a largely teleoperated controller environment. The mission of the newly commissioned policy and architecture committee would be to advance the robotic controller effort across the continuum from teleoperation to autonomy, and from individual robot control to the teams and swarms of robots envisioned for the future.

The discourse of architecture frameworks portrayed earlier revealed that no enterprise can be expected to be omniscient and develop an architecture from the absolute top. Good architecture practice borrows from both bottom-up and top-down views of what is to be accomplished and what can actually be accomplished. The technology for paving two lane roads in the 1940s preceded the advent of the Interstate highway inaugurated in the 1950s. In the 21st century there is now a vision of smart roads using radar and real-time systems to direct the flow of traffic which few could have predicted sixty years ago. Similarly, the advancement of Moore's Law and the aforementioned nanotechnologies will beget functionality and intelligence for robotic applications which really cannot be foreseen with any certainty today. Our prediction of the future is not as acute as we sometimes believe, and programs of record which span a decade of development or more, fail to take full advantage of technology insertions when they appear, relegating them near obsolete when the are fielded. The present and future technology cycle times are shrinking. Consequently, it makes sense, as the panel recommended, to "build a little, test a little" along an evolvable robotics controller architecture driven by policy and prudent investment with a long range vision of the future employment of military robotics on the spectrum towards full autonomy.

The study turned to at least one methodology that has such a charted course with a deliberate goal of consolidating existing platforms to a more manageable number. This study embraces an incremental approach towards commonality for two specific reasons: (1) as stated earlier, a pure top-down architectural design is not feasible for most enterprises since span of control/influence and budget are simply not great enough to encompass all that is and potentially will be in the future; (2) the ability to foresee the future beyond two Moore's Law cycles (approximately 3 years in total) is historically infeasible since disruptive technologies appear without notice in the present era of invention. Consequently, an approach towards incremental consolidation and advancement could be a sufficient model towards common robot controllers. For this reference model, the study turns to the Army's Communications Electronics Lifecycle Management Command's Battle Command Program and recognizes that a series of transitions can manage consolidation over time (see Figure below).

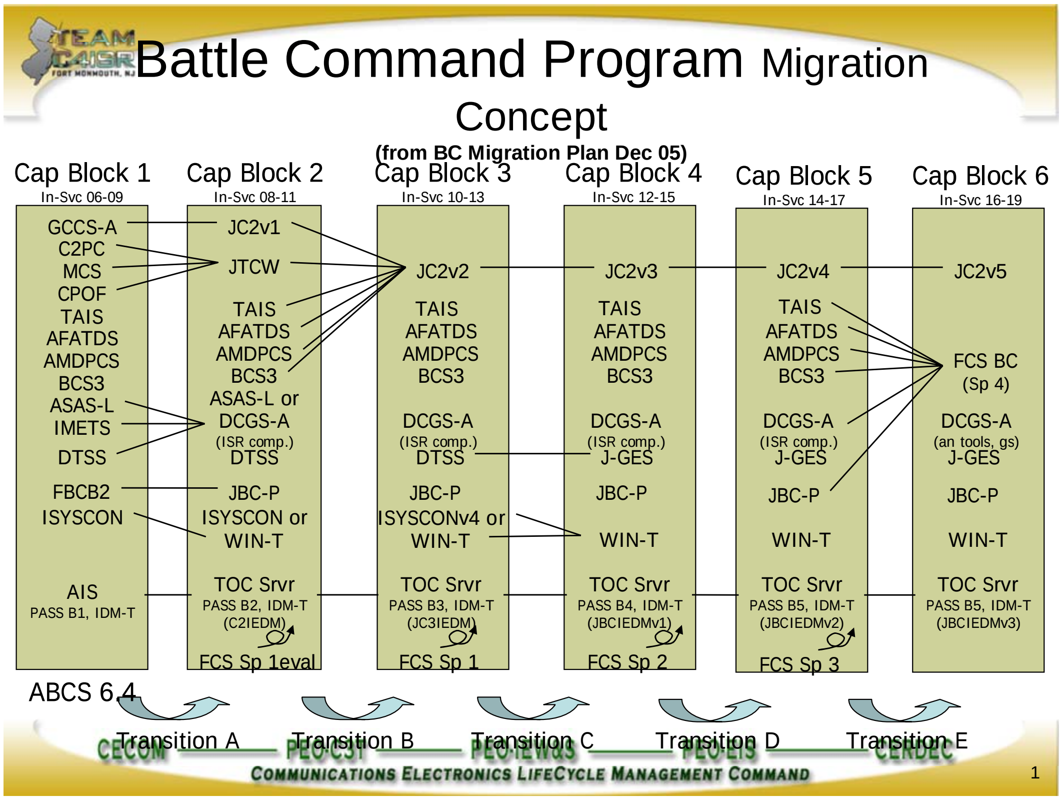


Figure from Ft. Monmouth Battle Command Migration Plan

The pursuit of a common controller for robotics fits this Battle Command model well. In a field which initially saw a variety of products with unique architecture and functionality, a methodical approach (coupled with strong program manager, leadership, policy, and smart investment) can converge to a simpler array of platforms. Note that the Battle Command Program also incorporates FCS spirals. A common controller program should be designed to do so also.

This section now refers back to its earlier premise and the figure presented in section 3. As surmised by the JAUGS briefing, the need for human decision (and thus human actuated controller) is diminished as artificial intelligence/autonomy is embedded in robotics. Thus coupled with the above Battle Command Program model for incremental consolidation, insertion points for “more intelligent” robotics will appear as technology and innovation provide opportunities for more on board AI. The synergistic effect of these two processes (incremental consolidation and AI growth) is an optimistic predictor for the future arrival of common controllers. Thus, a more holistic view of the dynamics of this process vice investment in individual specific controller consolidations will provide a greater return on investment in an era of budgetary constraints. The panel, as stated in the preceding section, reviewed some very specific platforms and progress to date found at each tab in Appendix A. To invest in creating a controller with the right number of joy sticks or buttons or displays as found in some efforts would provide less progress at greater expense than what the next emergent interface might provide, taking us nearer to our goal. Recall that the panel saw a preference for voice commands vice toggle switches and, more specifically, robots that were led the way soldiers lead and not like technicians, or as we again paraphrase Dr. Joe Braddock here, *to make the controlling interface act more in line with how infantry soldiers actually fight (in essence, less like a technician sitting behind a computer console).* It would be the loftiest of goals for a controller of any sort to be not existent at all, not too mention common. It is the "uncommon" controller that should sit at the end of the migration path.

This study pondered and analyzed the conditions of the present and the view of future. The expected and exponentially increasing technological advancements over a fifteen year horizon allow for a conservative prediction of evolutionary convergence towards commonality of controllers and increased autonomy of platforms. However, a simple "do nothing" approach, though it could be expected to yield desired results over the long term, might not produce these results in time enough. Consequently, specific recommendations are outlined in the following chapter to hasten the advancement of common controllers for unmanned platforms.

5. Conclusion and Recommendations

Conclusion:

This study hesitates to draw final conclusions. Indeed, there are many efforts underway universities and government laboratories (although disjointed and independent to a large degree) that are investigating the aspects of the future of robotics discussed here. A partial list of some of this work is found at the bibliography. Many have been refereed and presented at a variety of conferences. People and institutions are thinking and conducting research about the robots and robotic controllers of the future. But universities and laboratories do not set policy nor funnel investment beyond their own purview. And yet, a survey of some of their work by this study recognizes that there is a body of knowledge being built in this arena. This bodes well for realizing the incremental advancements in robotics across the JAUGS spectrum towards autonomy and AI. In the words of computer scientist Alan Kay, "the best way to predict the future is to invent it." Yet invention does not in itself yield production nor standardization. The efforts of Thomas Edison bear this out. To put the invention of the electric light bulb into practical use, an entire industry of electric power production and standardization had to be established. That industry required an architecture as will the robotics industry of the future.

From this analogy, the study concludes that the mere invention of new functionality in robots in the operational domain does not and cannot be a rational means to further the necessary advancements in common robot controllers. In all likelihood, commercial practice will produce the usual stovepipe applications, just as the number of video/stereo remote control devices stack up on the home coffee table. Commonality requires an architecture framework which demands an investment for that future. Commercial products hinge on profitability. Investment in commonality detracts from profit margins and, therefore, industry does not usually lead the charge unless there are incentives to do so or penalties for non-compliance, usually with the support of law.

There are clear reasons why the DoD and Congress would want a common robot controller for future robotic applications. Threaded in the earlier sections of this study, they are encapsulated here.

- Duplication or redundancies denote higher costs
- Commonality achieves soldier training efficiencies
- Migration to standardization achieves focus on the mission
- Common controller migration away from teleoperation is essential to the future robotic employment vision towards autonomy
- Common controllers are a forcing function towards greater understanding of how the future force wants to employ robotics
- Common controllers simplify the man-machine interface
- Controller simplification will free warfighters from dedicated robot control

- Common controllers will enable robot teams, swarms, and self-cooperation

Therefore, in order to realize the undeniable benefits of common robot controllers, certain steps are recommended to the JGRE to hasten this migration. At the product level, which primarily involves robots at the operational level of warfare today, some resistance may be expected from industry in self-interest. However, as in other industries such as communications or automobiles, such resistance can be overcome by incentives, policy, legislation or a combination of these factors. Some industry members of this study's panel professed voluntary migration to common controllers, but there were caveats with regard to preferred software languages or the sharing of corporate intellectual property.

Recommendations:

1. Develop a common robotic controller architecture. This undertaking is strongly recommended and deemed essential. Any enterprise, particularly as it advances in complexity requires a blueprint upon which to build. This study found no such architecture for common robotic controllers. As such, controllers are found to be followers, not leaders, for the industry in general. The application of robots goes far beyond individual teleoperated robots. How the warfighter interfaces with robots in the future, both in number and complexity, will outstrip the relatively simplistic technologies employed today. The vision for man-machine controller interface is a technology in itself which must be built on successively more complex interfacing techniques. The migration path to each stage of complexity, coupled with a vision of technological advancement timeframes, must be incorporated into a codified architectural framework.

2. Produce a common controller migration path. Evolving to the next stage of commonality among robot controllers requires a migration path to get from the disparate unique controllers to common layouts, switches, and displays. Tests have demonstrated warfighter preferences for the physical representation of the man-machine. However, much effort is needed to perform true ergonomic studies and human behavioral research. Such research could be conducted with the class of controllers already in production today and migrate to a common controller for many existent systems. The migration path should start with the present and utilize the output for lessons learned for next generation controllers.

3. Establish a repository for common controller efforts and robotic futures. There are a considerable number of academic research efforts and published papers on the subject of common controllers, robotic autonomy, and experimentation. These efforts can be found in professional journals, conference proceedings, and university websites. The JGRE should take on the challenge of indexing and creating a repository of such activity in order to promote sharing information

which should lead to faster convergence towards a common controller. No central repository was found by this study despite the availability of literature.

4. Advance research on human-robot cooperative environments. The notion of robotic control must necessarily migrate away from teleoperation towards greater robot autonomy. Autonomous robots will also be self-cooperating among themselves in the form of units of action, swarms, and other robot system configurations as advances in artificial intelligence progress. How warfighters interface with the increasing "intelligence" of such robots and robotic systems is not known. A common controller might be voice command, a glove movement, or any number of imagined future technologies yet to be invented much less tested. "Holodeck" simulations and other such virtual environments could begin to test cooperating human-robot interfaces now in advance of physical products. In this manner, the services can begin to gather human psychological acceptance, reliance, and control parameters before such systems are actually built.

5. Recognize and invest in activities which advance common controller efforts. The JGRE can reward those activities which are actively the driving force and leadership behind the advancement of common robot controllers. DARPA has gained notoriety with its Grand Challenge to promote autonomous vehicle navigation. Such challenges spawn cooperative groups, novel ideas, and a steady pursuit of a common goal. Similar incentives can be given to promote common controller activity in the form of realizable controllers for multiple robot applications.

6. In conjunction with the services, write the doctrine for future robot employment. The Office of the Secretary of Defense has produced an Unmanned Systems Roadmap, 2005-2030, for the purpose of outlining the current desired direction for the application of robots. No corresponding doctrine could be found underway in the services which incorporate how robots are to be employed, trained with, or relied upon. Doctrine is the warfighters' codification of the way they fight. From doctrine, the entire array of the remaining elements of the DOTLMS-PF paradigm is determined. Some of these elements require significantly long lead times to actuate. Consequently, those that have ownership of the robotics domain of activity must convey that future state with the writers of doctrine for robotic employment. To some extent, doctrine for the present "in theater" employment of robotics is lacking. The services must ensure that doctrine precedes employment as best as possible.

All of the above recommendations are useless in a vacuum. They each must be led by competent authority and knowledgeable persons that understand the robotic arena and the growing requirements for that arena. Chief among these requirements are common controllers for each successive migration stage of robots as they evolve from primitive teleoperated machines to autonomous/intelligent fighting partners. Fail safe operation of autonomous robots must be assured. Command and control in the field of robotics is truly yet to be explored. To guide JGRE through the full spectrum envisioned for robots, it is recommended that the JGRE establish a small free-standing permanent committee of two or three experts augmented by both the government and commercial communities. This committee would steer the aforementioned recommendations, adjust accordingly, and lead both the fiscal and policy efforts in the common controller efforts for the JGRE. A natural tendency would be for the committee to become a subset of JAUS. However, this study cautions against that move at this time until some degree of focus on the subject has been created and exerted as an independent group.

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