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Abstract

Government research programs often support the advancement of technologies with strategic commercial potential in order to enable building industrial activity in new areas of technology. For example, considerable current government research funding for co-robots, or robots that interact with and help individuals, is motivated by the projected needs of aging populations in industrialized nations. Innovation theory offers one approach to analyzing government support of research as an economic development strategy. Analysis can improve understanding and support efforts to improve its effectiveness. Therefore we analyze this technology policy strategy from the perspective of technology innovation theory. In the United States, a robotics roadmap document motivates the National Robotics Initiative, which is a set of funding programs offered by multiple government agencies. We find that some aspects of the NSF's effort, and those of other countries, accord well with insights provided by innovation theory, while others less so, and that increased awareness of innovation theory could help inform government technology policy in the U.S. and elsewhere.

1. Introduction

ROBOTICS HAS ALWAYS INSPIRED the vision of autonomous entities that would create a seismic shift in economic productivity, increasing it without obvious limit by providing labor at minimal cost. While at one extreme this could make everyone rich, at the other it could throw much of society out of work and into poverty. Regardless, Adam Smith's invisible hand suggests an inevitability to advances in robotics, if these advances are technically feasible. The view that such advances are in fact feasible has been buoyed by progress in robotics in the modern age.

There is a successful track record in industrial robots, the first robotics area to make significant inroads into society. More recently, robotic airplanes and other military robots have become increasingly important. Currently, service robotics is becoming a major emerging focus of robotics research in the belief that need will successfully drive technical advances and commercial growth. Supporting this belief, sales figures in recent years indicate a foundational infrastructure of robotics production that is vigorous enough to grow quickly to meet demands [1].

The prospect of promoting future economic development is often a factor in motivating governments to invest in funding for research programs. Thus, a number of national governments have identified robotics as a key emerging economic growth area for which governmental research and development support would be in the national interest. For example the European Union [2], the Netherlands [3], Taiwan [4], Korea [5], Japan [6], and the United States [7] all have produced strategic documents analyzing prospects and providing guidance to national efforts.

The need for service robotics is exemplified by Japan's JSTAR report [6], which is motivated by demographic changes projected in Japan that will make eldercare unprecedentedly important. Related in spirit to Japan's 1982-1992 ambitious Fifth Generation Computer Systems project [8], this new project differs crucially in addressing a clearly defined demographic need. Similar demographic changes are in fact projected to occur in many developed nations in the years and decades ahead (Figure 1).

The U.S. created the National Robotics Initiative (NRI) in 2011 to support research and development of "co-robots," robots that work cooperatively with human partners [9]. Several government funding agencies support the initiative. These include the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), the National Institutes of Health (NIH), and the Department of Agriculture (USDA). Although the overall goal of the Initiative is to "accelerate the development and use of robots in the United States that work beside, or cooperatively with, people" [9], each agency has its own funding focus.

The NSF component of the NRI, like much of what the NSF does, emphasizes basic research. The focus is on areas that have been identified as potentially relevant to producing flexible and adaptable robots that display significant intelligence. A large number of research problems were identified as suitable for funding, consistent with the complexity of the robotics field. Among these, the NSF solicitation adopts the methodological approach of facilitating building better toolkits for robotics developers [10]. In particular, it emphasizes the development of open architectures with "common hardware and software platforms" and a standard set of interfacing protocols. These tools will be available worldwide. Along with this, the NSF proposes to make publicly available a database of software, hardware, and tests that “citizen engineers” can easily access.

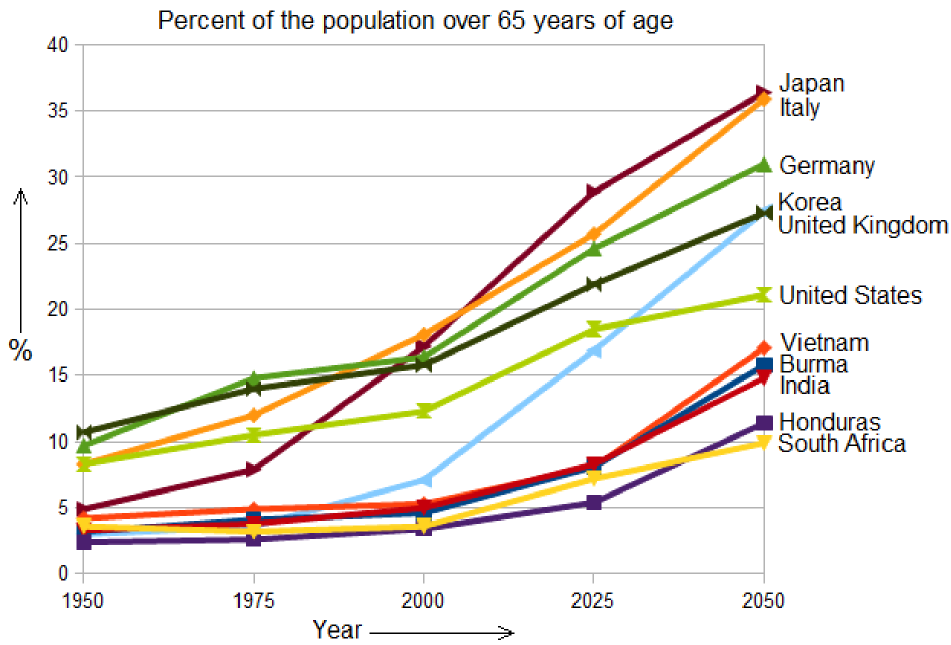

Figure 1. Aging of population for selected countries [11].

Innovation, Innovation Theory, and National Robotics Policy

Government research typically assumes that innovation is useful for improving life in society. Yet there is a large body of work on innovation that is usually not taken into account in designing these research programs. To show the importance of this work, we examine the National Robotics Initiative research grant solicitation of the National Science Foundation [10] as an example. This is useful because using innovation theory to better understand research funding programs may ultimately prove useful in designing them to better meet the goal of national economic development.

Innovation is defined in different ways by different fields, leading to confusion over its meaning. The NSF views innovation as an integral facet of its mission [12] and even has a Science of Science and Innovation Policy funding program [13]. While the NSF uses the term quite broadly, in the context of innovation theory an innovation can be better characterized as *an invention that is implemented* [14]. Such innovations have three components:

1) a degree of originality, either in defining a problem or solving a problem;
2) a solution appropriate to the problem; and
3) an implementation.

Therefore, in this article we use innovation to refer to an original idea that solves a problem (an invention) that is implemented. An innovation can be a product or process, and it can have measurable economic impact.

Why use Innovation Theory?

Economic growth depends significantly on the innovation rate of a society [15]. Consequently, a motivation for the NRI is promotion of innovation in the U.S. in service robotics, in the belief that innovations in this area can be accelerated enough to have a sizeable economic benefit. Consistent with this, one goal of the NRI is to spur innovation in the area of robot-human cooperation, or co-robotics.

Nevertheless, the NRI was created largely without reference to innovation theory. It is based mostly on analyses found in *A Roadmap for US Robotics—From Internet to Robotics* [7]. The *Roadmap* assesses the prospects and opportunities for advancements in different sectors of the robotics industry. There are two overarching themes in the report:

1) Demographic changes towards older populations in the developed world are driving an increasingly urgent need for robotic devices.
2) Robotics are projected to be an important factor in the future economic prosperity of the U.S. The report also notes explosive recent growth in sales of service robots, in both the professional and personal market segments.

The U.S. Roadmap was put together by a large number of robotics specialists from academia, industry, and national laboratories. It was greatly influenced by earlier works that it cites, notably the *Office of the Secretary of Defense Unmanned Aircraft Systems Roadmap* 2005–2030 [16] (updated for 2011–2036 [17]) and the *WTEC Panel Report on International Assessment of Research Development in Robotics* [18]. This represents a considerable accumulation of expertise in the field.

On the other hand, many of the U.S. Roadmap participants had vested interests in its recommendations. Since the roadmap was intended as a path forward for U.S. funding for robotics research, there was a built-in incentive for many participants to ensure that their areas of expertise were well represented, rather than make fully impartial assessments or proactively seek dramatically new directions. Nevertheless while conventional wisdom can often predict near-term futures in existing markets and research areas, it risks falling short in foreseeing new markets and ways of doing things [19]. This tendency can be counteracted by including experts in other relevant areas. For example, with aging demographics seen as a driving force in expanding the service robotics market, having gerontologists on a panel could provide a valuable perspective on future needs for robots in homes and workplaces.

2. Innovation Theory and the NSF Initiative

Most R&D is used to solve specific problems [20]. While solving specific incremental problems can be an important part of enhancing technical capabilities, it is not in and of itself sufficient to realize the economic benefits of disruptive new technologies [21], such as is foreseen for co-robot commercialization in the U.S. Recognizing this, the Organization for Economic Co-operation and Development (OECD) recommends a broad range of innovation strategies that include demand side policies [22].

The innovation theory-based analysis of the NSF portion of the NRI presented here focuses on a demographic shift, the aging population of the industrialized world. This aging problem is projected to be less pronounced in the U.S. than in many other countries. Since commercial activity tends to follow need, the need for co-robotics to assist the elderly is expected to be more severe abroad than in the U.S., driving the corresponding industry abroad more vigorously. This in turn suggests that while the NSF toolkit-based strategy for funding basic co-robotics research is likely to facilitate commercialization, demographic projections will provide a greater incentive for foreign companies than to U.S. companies to try to benefit. While this is a good thing overall, it is also somewhat unanticipated and worth exploring. One way to do this is to examine the situation through the lens of innovation theory [18]. Some leading approaches to innovation theory are reviewed next.

Evolutionary Theory of Innovation

The evolutionary theory of innovation is based on evolutionary economics, explored for example by Verspagen [15]. In one version of this theory, advances in technology are treated as random changes to what currently exists. Economic growth is considered to be related to three factors:

1) the standard deviation in the distribution of plant productivity, considered a measure of how much innovation is occurring;
2) the savings rate; and
3) the speed of diffusion of ideas.

The NSF solicitation [11] clearly supports factors 2) and 3), for example stating, "… for broad diffusion, access, and use (and hence, to achieve societal impacts), co-robots must be relatively cheap, easy to use, and available anywhere." The solicitation also promotes diffusion of ideas, saying that "Collaboration between academic, industry, non-profit and other organizations is strongly encouraged …"

A deeper understanding of diffusion can shed additional light. Diffusion can take several forms [23]. The two forms most relevant to the current discussion are diffusion within a market, and geographical diffusion.

- ***Diffusion within a market.*** Innovation cannot be taken out of its existing environment because advances occur based on what currently is in place. Innovations that are viable in the marketplace evolve as they diffuse within the market [20] [24] and are applied to specific jobs [25]. It is the marketplace that decides whether an innovation survives and how successful it becomes, and success depends on many factors. These include luck and marketing, besides the intrinsic strength of competing solutions. If an idea or product can be copied, as is encouraged by the open architectures advocated by the NSF, that will magnify the influence of the collateral assets of a company (*e.g.* the sales force and marketing operations, distribution channel strengths, and supplier relationships) in determining who controls the market [26].
- ***Geographical diffusion.*** An important question is the degree to which benefits of U.S.-based robotics research, which is the focus of the NSF effort, will accrue to the U.S. robotics industry compared to competing foreign industry. This cannot be known for

sure ahead of time. However, another technology that began as a relatively siloed scientific domain but then crossed disciplinary boundaries, some of which provided commercial applications, forms an exemplar of the model that the NRI appears to envision for robotics. Leydesdorff and Rafols [23] found that siRNA (small interfering ribonucleic acid) research provides such an exemplar. Work on siRNA was performed at major universities in different countries. Robotics research is also international. For example, the major robotics conferences ICRA (International Conference on Robotics and Automation) and IROS (International Conference on Intelligent Robotics and Systems) are both explicitly internationalized. According to Leydesdorff and Rafols [23], siRNA research has been "fully globalized," has "entered a phase of commercialization," and is "potentially useful to many applications …" The analogy with what the NRI and other nations' funding programs hope for robotics is clear. If that analogy continues to hold in the future, worthy research funded by NSF will become known, accessible, and used by robotics researchers and entrepreneurs around the globe.

Customer Centered Innovation

Customer centered innovation is based on the observation that *people buy and use products because they have a job they want to get done*. This approach has been explored by *e.g.* Christenson and Raynor [27] and Bettencourt and Ulwick [28]. New products are judged by how well they do that job compared to current solutions [29]. Thus, innovations cannot be effectively examined without taking account of the marketplace, because competition among solutions determines what products survive and succeed. Applying this general framework to robotics predicts that the success or failure of the next generation of robots will be tied to the jobs they will perform and the alternatives available for doing those jobs.

The NSF program does promote competition among alternative solutions proposed by different researchers with its practice — typical of NSF research programs — of competitive peer review. However it is unclear how this process can effectively judge value independent of market mechanisms, which automatically balance technical criteria with all the other factors that are key in the marketplace such as cost, ease of use, etc.

Value Chain Evolution Theory

The value chain evolution theory approach considers the factors by which customers choose products to be prioritized as follows: 1) functionality, 2) reliability, 3) usability, 4) customization, and 5) price [27], [30]. The NRI indicates that not even the first of these, robot functionality, is good enough yet for the next generation of applications [9].

The other end of the scale is when customers are fully satisfied with the functionality, reliability, usability, and customization of a product. At this point the technology is well understood, and price becomes the deciding factor. Now the field becomes susceptible to technologies that are disruptive due to lowered costs. One approach to greatly reducing costs is to institute industry-wide standards that define a technology. When appropriate standards exist, whether official or de facto, some companies can focus on commoditizing individual components or modules associated with a whole solution. The cost reductions enabled by this commoditization can cause disruptive developments in the industry by replacing the market for high-priced integrated systems made by a single manufacturer with a market for lower-cost systems made by companies that assemble commodity modules made by other companies.

A widely recognized example is the PC and laptop markets, where manufacturers now mostly assemble commodity components purchased from other companies. Another example is the Ethernet, a system component the commoditization of which enabled its rapid diffusion as a communications network solution into domains from PC networks to cell phones [31]. A third example is the PCI Express bus, a component used in personal computers [31]. Shifting back to the system level, a visit to any home improvement store reveals that modern homes are now constructed using a plethora of standardized commodity components ranging from wooden 2x4s to doors, HVAC components, plasterboard wall panels, electrical system parts, and so on.

The NSF solicitation promotes the eventual commoditization process because of its explicit promotion of research that results in toolkits, which can be used by other research groups and thus form de facto preliminary proposals for standardization of components.

Three-Stage Technology Evolution Model

A three-stage technology evolution model, a model of how new markets develop, is described by Abernathy and Utterback [24]. The first stage is called the *fluid* phase, in which a large amount of experimentation occurs to find the right technology and market approach. This is a phase where market competition determines which strategies and technologies survive and succeed. Research efforts associated with academic institutions, like the NRI (including its NSF funding program), help support the early stages of this phase. After a winning approach has been determined by the marketplace, the next stage begins. This is the *transitional* phase, which occurs when a market and technology are understood well enough that standards can be set and productivity increases. The final stage, called the *specific* phase, is where one technology comes to dominate the market.

Remarks

Often academic researchers do not benefit directly from innovation and thus are not effectively incentivized to follow through with the technology transfer of their scientific advances. One reason is that academics often do not have the right skill set to commercialize research breakthroughs, and these breakthroughs are generally not formulated in the framework of commercially important jobs to be done. The specific knowledge needed to translate an advance from R&D into a commercial product is sticky, meaning only a few people have the specific knowledge necessary to do so [32]. Forming the right partnerships is therefore crucial in this process. Recognizing this, the NSF solicitation encourages academia-industry partnerships. In addition, other NSF programs encourage commercialization of research results, notably through programs associated with the Industrial Innovation and Partnerships Division (http://www.nsf.gov/div/index.jsp?org=IIP).

3. Further Analysis

Let us focus next on understanding the NSF's NRI solicitation with respect to innovation theory from the standpoint of two key dimensions: (1) the demographic changes that will increasingly drive the co-robot marketplace, and (2) the NRI emphasis on open architectures.

A Demographic Driver of Robot Development

According to the *Roadmap* [7], a major driver of growth in the demand for service robots is the aging of the world's population, especially in the developed world. Indeed, Figure 1 (shown earlier) indicates that several countries are projected to have more than one quarter of their residents over age 65 by 2025. The NRI and its NSF solicitation are consistent in indicating that the aging of the U.S. population is a major force spawning the need for future robot applications. The aging issue has implications for several sectors of the economy. First, an aging population requires more health care [33]. Second, an aging population needs more help in living independently. Traditionally, this is done by having family members, day companions or healthcare workers provide assistance as needed in elderly households. In the U.S., retirement communities are popular because they provide help in meal preparation, cleaning, transportation, and other endeavors. Figure 1 showed the specific percentage of the population projected to be over 65 for various countries, with numbers currently growing at rapid rates.

Another way of looking at demographic change is through the support ratio, which is the number of working-age adults (age 20 to 64) for every person of retirement age (65 or older). Most developed countries are projected to experience dramatically declining support ratios between now and 2050, with the OECD member country average declining to 3 around 2025 and 2.1 around 2050. The U.S. is slightly better off with a less severe decline to 2.6 by 2050 [34]. The trend toward reduced numbers of workers per retired person will necessarily have a major economic impact under the traditional eldercare paradigm, but this could be mitigated by the emergence of co-robots that perform eldercare work previously handled by humans.

Because the U.S. will be less severely impacted by the graying of its people, other countries will see these effects sooner. Figure 2 plots projections of the inverse of the support ratio (*i.e.* the ratio of retirement age people to those of working age) for several developed countries and Figure 3 plots the same for the U.S. and several developing countries. This ratio gives the same information as the support ratio, but helps visualize the issue. Here, lower values are more desirable from an economic standpoint. As can be seen, the U.S. is in better shape than many developed countries. This advantage is projected to continue for the foreseeable future. Indeed, the situation for the U.S. in 2050 is more favorable than the situation for Japan even now (although the developing countries are still better off in this regard than the U.S.).

The inverse support ratio trends suggest that other countries may disproportionately reap the benefits of commercialization of assistive co-robots for the elderly compared to the U.S. This is because innovations are usually developed for lead users [35], who are among the first to benefit from solving problems that will eventually grow in importance to the rest of society [22]. That process is enabled by the international character of robotics research and, by analogy with siRNA technology [23] as described earlier, its projected international commercial diffusion. Should demographics drive expansion in the robotics industry, Japan will be a leader in the industry as the first country to face the need, followed closely by several European countries. The U.S. will lag demographically, and due to the consequently relatively lower incentivization, perhaps trail in the robot market segments driven by these demographic changes.

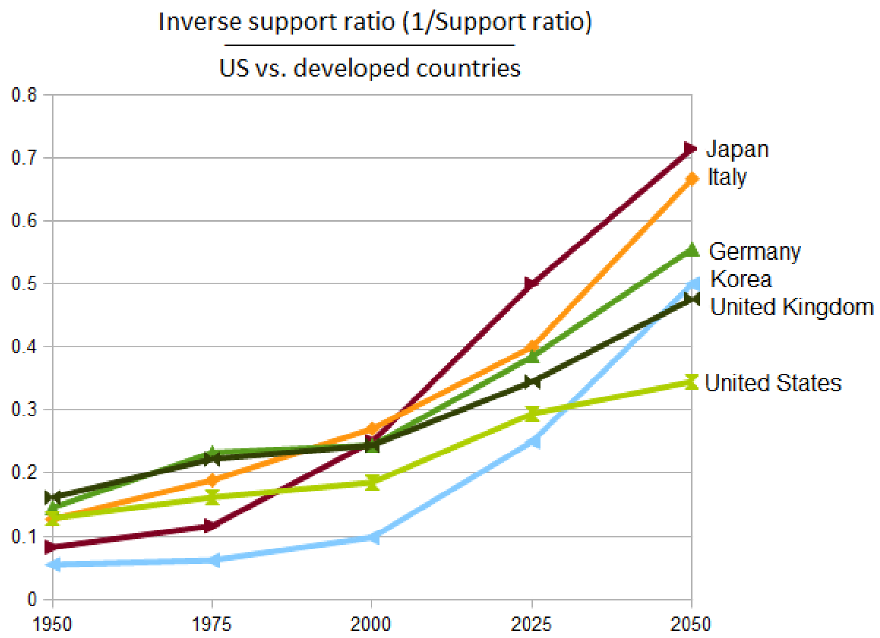

Figure 2. Inverse support ratios (ratio of retirement age people to those of working age): U.S. and selected other developed countries.

From Demographics to Niche Robotics Markets

Innovations often start out in niche markets [19], [36]. These new inventions are then modified, improved and re-defined as they move through the marketplace [25]. Because niche markets are generally small, the potential profit in a niche is often not initially enough to attract the attention of large, established companies [19]. Thus, these small markets are relatively protected, providing a small company the breathing room to develop the culture and values necessary to successfully compete. One example of a robotics niche market that developed to meet demand is robot lawn mowers. Europe is the leader in sales of such devices, while the U.S. remains far behind. The reason for the demand in Europe is thought to be the relatively high cost of landscaping services, while in the U.S. the lower cost of such services has dampened demand [37].

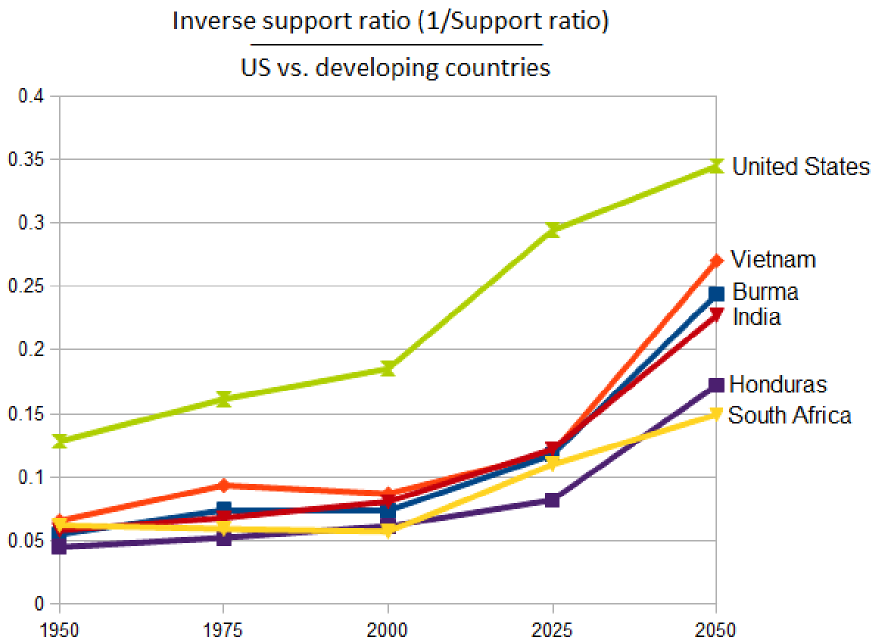

Figure 3. Inverse support ratios (ratio of retirement age people to those of working age): U.S. and selected developing countries.

A small company develops collateral assets (such as supplier, distribution, sales and marketing resources) as it supplies a new market. With assistive co-robots for the elderly defining a niche that is expected to provide even more opportunity for companies overseas than domestically, foreign companies will be relatively more incentivized to lead in colonizing the new markets. The collateral assets of some of these niche companies will grow with the companies and allow them to establish themselves as larger, mainstream, multinational companies as they mature over time. These companies will then have the assets to fight off new entrants [26] [30]. Exacerbating this problem for late entrant U.S. startups are language, cultural, relationship, and distance challenges for U.S. companies entering European and Japanese markets.

Effect of Open Systems on the Robotics Industry

As noted earlier, the NSF funding program emphasizes development of toolkits that support robot engineering. This strategy of promoting an open systems approach also necessarily encourages development of de facto standards for the robotics industry. On one level, this strategy seems well designed for advancing the field generally, since innovation tends to occur when there is recognition that the tools available are capable of solving a pressing problem [38], [39]. However, the Abernathy and Utterback model described above [24] suggests that this focus may be premature because it will result in standards for the next generation of robotics which have not yet experienced the fluid phase of market competition to help determine them. It is thus not clear whether standards that may result from the NSF funding process will be ideally suited to future market demands.

Suppose we optimistically assume that good de facto standards do result from the NSF emphasis on toolkits. Such standards for human-robot systems may stimulate technological advances in the co-robot area because the tools developed will be freely available worldwide. Market forces will then likely determine where commercialized robotics innovations occur.

A major market force is the demographics of aging populations. This force favors Japan and Europe over the U.S. because Japan and Europe will face the need for robots to help support aging populations sooner than the U.S. faces this need. Innovation theory suggests that, with more pronounced aging of their populations, those countries will have the structural advantage over the U.S. of greater incentives for co-robot development and commercialization, increasing the likelihood of companies in these places being the first to commercialize robotics technologies that address the market needs of aging populations. Thus the open toolkit strategy could help the robotics industries in other countries even more than the robotics industry in the U.S., although the goal of the NRI is to accelerate robotics and its commercialization in the U.S. Of course, even if foreign industry benefits, U.S. industry may also benefit, thus satisfying the funding program's goal. Overall, facilitating robotics commercialization worldwide is a broadly positive thing.

Concluding Thoughts and Recommendations

The NSF solicitation envisions the creation of flexible co-robot systems that rival humans in their ability to adapt to situations they encounter. The robots must not only be capable, but also "relatively cheap, easy to use, and available anywhere" [11]. The goal is to accelerate the development of robot systems that work cooperatively with people.

Given this vision, the NSF's NRI funding program does certain things well from the viewpoint of innovation theory. One example is that the envisioned open architectures and repositories of software and hardware encourage the dissemination of information by making the tools created under the solicitation available to a worldwide audience.

Another example is that the solicitation encourages collaboration between industrial developers and researchers. This helps overcome the problems of technology transfer, such as the common situation in which no one person or organization has all the knowledge necessary to produce a commercial solution to a problem.

A third example is that the NSF's funding program encourages competition among groups in solving certain problems, with the important caveat that these are not problems defined by the marketplace.

Are there specific areas where the U.S. has an advantage over other countries? One may be health care. While health care and eldercare overlap substantially, they are far from identical. Figure 4 shows the percent of average salaries and wages, adjusted for purchasing power parity (PPP), currently spent on health care. The U.S. spends over 15% of salaries, while the next closest country, Germany, spends below 11%. This presents an environment in which U.S. companies have a relatively greater incentive to take the lead in developing robots that reduce the costs of health care, analogous to the demographic environment which incentivizes industry in other countries to take the lead on eldercare co-robots as explained earlier. Although the NSF solicitation does not address health care directly, because the NSF as a whole does not address health care directly, the National Institutes of Health also participates in the NRI and does target research funding for robotics related to health. One way the NSF effort could potentially target the seeming U.S. structural advantage in commercializing robotic applications in health care might be to encourage development of toolkit architectures that recognize the projected technical needs of health care robotics.

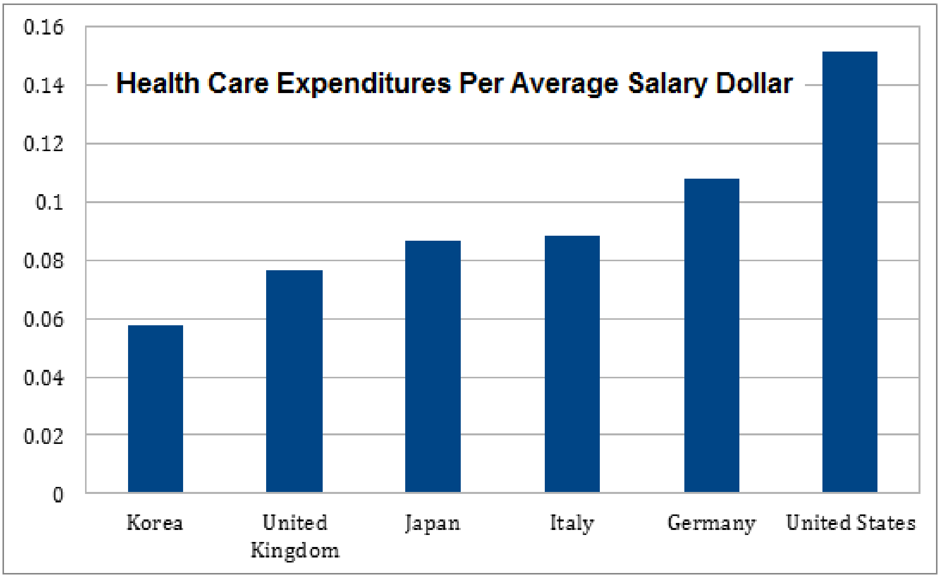

Figure 4. Health care expenditures (based on [40]).

Another area where the U.S. may have an advantage is in the distribution of goods. Indeed, there are already startup companies in this area, such as Kiva Systems. Part of the reason is salaries. Figure 5 shows average annual wages, adjusted for PPP, for several developed countries. The U.S. is over 21% higher than the next highest, the United Kingdom. The high wages paid in the U.S. make labor-intensive industries such as distribution potentially attractive areas for robot innovation. With respect to distribution, there is already considerable interest in self-driving vehicles, which makes distribution a particularly promising application.

The sectors of eldercare, health care, and distribution exemplify the general observation that a shortage of plentiful, easily-available labor favors development and deployment of substitutes such as co-robots. In particular, eldercare and medical care are areas in which projected future needs threaten to outstrip supply in developed nations. This paper discusses the funding program example from the perspective of innovation theory. This is an approach that has been underutilized for this purpose. Further insights may be expected as innovation theory is applied to other related analyses such as designing science and technology funding programs in particular, and more broadly, technology policy at the national level.

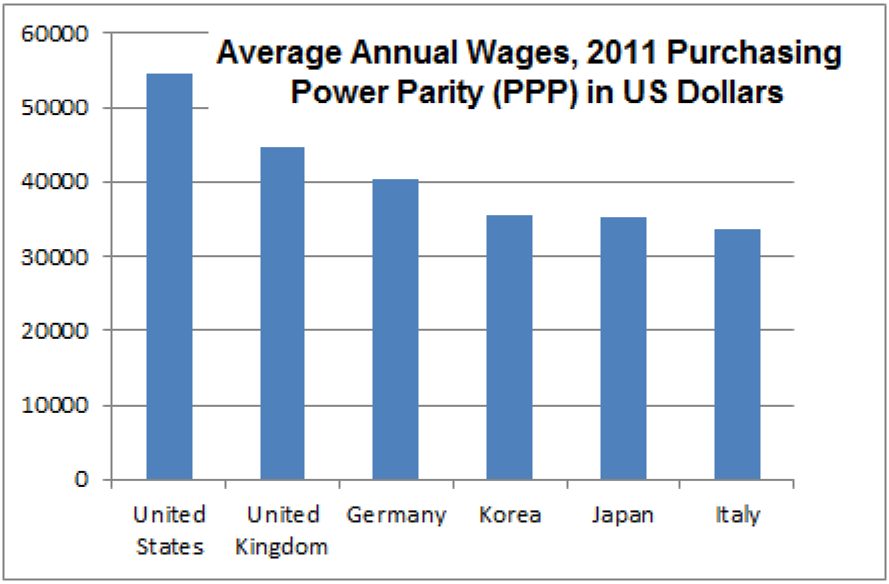

Figure 5. Wages, calibrated to purchasing power parity in U.S. dollars (from http://stats.oecd.org/Index.aspx?DatasetCode=AV_AN_WAGE).

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