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Supplementary Materials for

Progress in robotics for combating infectious diseases

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Supplementary Materials

Topic 1: Robotic Platforms Used in Practice

In this section, robotic platforms used in practice for the prevention and treatment of infectious disease are reviewed, including research platforms and available commercial products. The list in the Table S1 is not meant to be exhaustive and the systems mentioned below are only meant to be examples, while other emerging robotic platforms employed for the COVID-19 response can be found in (*171*).

1. Clinical care

· ***Biological sample collection***

Nasopharyngeal and oropharyngeal swabs are used for initial diagnostic testing for COVID-19, which requires sample collection, handling, transfer, and laboratory testing. However, the number of qualified medical staff for this process is limited. This leads to the demand of autonomous robots for nasopharyngeal and oropharyngeal swabbing (*20*).

A remote specimen collection robot, for example, was developed by Korea Institute of Machinery & Materials (KIMM). It aims at eliminating direct contact between clinicians and patients (*172*). The robot is composed of a master console controlled by medical staff and a remote robot equipped with a disposable swab. It can retrieve samples from the nose and mouth of patients.

· ***Telepresence***

iRobot and InTouch Health announced an alliance targeting healthcare in 2011 (*173*). The Remote Presence Virtual + Independent Telemedicine Assistant (RP-VITA) robot was unveiled in 2012 and had remote interactive capability between clinicians and patients (*174*). It has enhanced navigation capabilities based on environment mapping and obstacle avoidance tailored to hospital environments. In 2013, the FDA cleared RP-VITA as the first autonomously navigating telepresence robot in healthcare. It can be used during pandemics and after surgery (*175*), as well as for cardiovascular, neurological, prenatal, psychological and intensive care. InTouch also offered virtual assessment and monitoring of patients, providing virtual visits for the family members of patients (*176*). It is an important tool for bridging the physical distances during the pandemic while facilitating compassionate care for both patients and families (*177*).

There have also been extensive developments in remote operated ultrasound systems, like MGIUS-R3 (Shenzhen MGI Tech. Co., *Ltd.*, Shenzhen, China) (*39*) and 5G-enabled remote ultrasound solution (Siemens Healthcare GmbH, Erlangen, Germany) (*178*). A force-controlled ultrasound robot was also developed to fuse cross-modal sensory information from ultrasound and force measurements for remote diagnosis (*179*).

2. Public safety

· ***Temperature monitoring and emergency assistance***

Robots have demonstrated their capabilities in diagnosis and treatment for patients with COVID-19 (*180*). Mobile robots with automated cameras, incorporating thermal sensors to screen multiple people simultaneously in public areas for temperature monitoring, allowed retracing infected individuals and those in close contact. An autonomous robot, called Promobot (Huntingdon Valley, Pennsylvania, USA), was used to measure temperature and other vital signs and health parameters such as lung capacity, blood oxygen saturation levels, and blood glucose. The robot can operate in crowded places and provide quick tests to inform users about their health status (*181*). It also features facial recognition and is connected to other databases. Pulse oximeter can be used for checking oxygen levels, and is a useful tool for monitoring COVID-19 at home (*182*). The Cloud Patrol Robot (CloudMinds Technology *Inc.*, Beijing, China) (*183*) used infrared sensors that allow real-time temperature monitoring. Another AI-enhanced device from the same company, CITMS-200 (*184*), provided rapid temperature screening for groups of people. They are ideally suited for crowded places such as hospitals, hubs, and shopping malls. Dr. Spot, a quadruped robot, was also used to monitor vital signs in a contactless manner (*185*).

· ***Disinfection***

Although drones have been used for air disinfection of cities, there is no evidence about the effectiveness of outdoor disinfection for disease control (*186*). Instead, robotic disinfection of indoor environments demonstrates improved performance compared to manual cleaning in terms of reduction of the concentration of contaminants and the duration of the overall disinfection process.

To date, disinfection of unoccupied spaces is performed across multiple cycles, by positioning a single emitter in different locations in order to maximize the coverage. For instance, Xenex LightStrike Robot (Xenex Disinfection Services *Inc.*, San Antonio, USA) is one of the UV disinfection robots for SARS-CoV-2, the virus responsible for COVID-19 (*187*).

Recent examples, include robots like the UVD Robot (UVD Robots, Odense, Denmark) (*188*), are able to autonomously navigate and map the environment. Another alternative is based on distributed control of inter-connected swarm robots (Surfacide *Inc.*, Wisconsin, USA) (*189*), which enables a more efficient delivery of energy over a large area in a single cycle. Other functions of this system include a laser mapping feature to keep track of the disinfected surfaces and feedback on the reflected energy to estimate the amount of UV energy released. Other examples include Aertos 120-UVC (Digital Aerolus *Inc.*, Kansas, USA) (*190*) and TMiRob (TMI Robotics Co. *Ltd.*, Hong Kong, China) (*191*). However, all the aforementioned devices have a common limitation due to occlusion of the UV light.

To overcome this limitation, a flexible mobile manipulator was developed with enhanced disinfection capabilities (*192*). It was realized to operate semi-autonomously by modifying a robot previously designed to work in hazardous environments. It is equipped with multiple fixed lamps to disinfect open surfaces, like walls and floors, as well as a lamp driven around by a robotic arm for the targeted disinfection of hidden surfaces. A similar platform was developed under the name of Agile Dexterous Autonomous Mobile Manipulation System (ADAMMS) (*193*), while an analogous robot was also developed for chemical disinfection of human traffic areas (*194*). These systems incorporated an electrostatic spray at the end effector of the robot, which ensures an efficient distribution of the disinfectant over the target surfaces.

3. Laboratory and supply chain automation

- ***Delivery and logistics***

Many robots for delivery and logistics are based on autonomous mobile robots, and they have been increasingly used since the COVID-19 pandemic. The TUG autonomous mobile delivery robot (ST Engineering Aethon *Inc.*, Pittsburgh, USA), for example, was used to assist nurses by tugging carts or bins with medications, specimens or sensitive materials (*195*). It can interact with the users by a touch screen interface, and navigate autonomously. A humanoid service robot, Ginger (CloudMinds *Inc.*, Beijing, China), was sent to hospitals to help with admissions and education services (*196*). Self-driving vehicles like Nuro R2 (Nuro *Inc.*, Mountain View, USA) combined robotics and artificial intelligence to make contact-free deliveries to hospitals or labs (*197*). Robots can also be used for pharmaceutical distribution chains. For example, PharmASSIST ROBOTx (Innovation *Inc.*, New York, USA) is an example for robotic medical dispenser system, and can provide medication management solutions (*198*). The UDI vans, named as Hercules, was used for contact-less package transportation in China (*199*). Yumi was employed to assist the serological testing (*200*). The robot can automate the "pipetting" process repeatedly, which can reduce the workload of human operators.

Drones have also been used for delivery and logistics purposes. Terra Drone (TerraDrone, Tokyo, Japan) (*201*) and Antwork Drones (Antwork *Inc.*, Zhejiang, China) (*202*), for example, flies between disease control centers and hospitals for the transportation of medical samples and quarantine materials (*203*). The drones developed by MMC (MicroMultiCopter Inc., Shenzhen, China) were used for delivering purposes during the COVID-19 outbreak (*204*).

4. Out-of-hospital care, quality of life, continuity of work and education

- ***Home-based nursing***

Nursing robots can help clinicians to assist patients. Sanbot Elf (Omnitech, Padova, Italy), a multifunction robot, was used in hospitals during the COVID-19 outbreak (*205*). This nurse robot features voice/face recognition, autonomous navigation and can interact with patients to monitor clinical parameters and provide medications.

Nurse Assistant Robot Moxi (Diligent Robotics *Inc.*, Texas, USA) was used to assist nurses in terms of gathering supplies and delivery to patients (*206*). It can relieve the workload of nurses while maintaining the consistency of medical care workflow. It is also able to recognize and manipulate objects thus to gather supplies and deliver lab samples.

- ***Socially assistive robots***

Prolonged isolation of individuals from social interaction during COVID-19 may have a negative impact on mental health. In this case, continued social interactions can be deployed by social robots. Jibo, Pepper, Paro, Zora, and Buddy are all existing products for caring and social companion purposes. Some of them are equipped with touch sensors, cameras, and microphones, which enables their owners to interact with them. They can assist their owners in alleviating loneliness, keeping social interaction or

reminding about the medications. Robots are also used for interacting with the general public. For example, the virtual robot chatbots was used as a communication tool for travelers to obtain the latest travel guides, as well as access online health consultation based on AI techniques (*207*). Service robots were also used as a tool for physical distancing in tourism (*208*).

Table S1. Commercialized products for infectious diseases.

Robotic platform	Category	Company	Key features	Ref.
RP-VITA Robot	Clinical care	InTouch Health and iRobot, Santa Barbara, USA	Remote presence virtual and independent telemedicine assistant	(*174*)
MGIUS-R3	Clinical care	Shenzhen MGI Tech. Co., *Ltd.*, China	Remote real-time diagnosis, combines robotic technology, remote real-time control system and high-resolution ultrasound imaging	(*39*)
5G-enabled remote ultrasound solution	Clinical care	Siemens Healthcare GmbH, Erlangen, Germany	Provide the best possible support to healthcare providers at each stage of COVID-19 patient care	(*178*)
Promobot	Public safety	Huntingdon Valley, Pennsylvania, USA	Measure temperature, lung capacity, blood oxygen saturation levels and sugar	(*181*)
Xenex LightStrike Robot	Public safety	Xenex Disinfection Services *Inc.*, Texas, USA	A pulsed, high energy, broad spectrum UV light technology	(*187*)
Aertos 120-UVC	Public safety	Digital Aerolus Inc., Kansas, USA	An indoor drone with UVC energy	(*190*)
TUG autonomous mobile delivery robot	Laboratory and supple chain automation	ST Engineering Aethon, *Inc.*, Pittsburgh, USA	Transport goods, materials and clinical supplies within the hospital	(*195*)
PharmASSIST ROBOTx	Laboratory and supple chain automation	Innovation, New York, USA	A robotic medical dispenser system with medication management solutions.	(*198*)
MMC Drones	Laboratory and supply chain automation	MicroMultiCopter, Shenzhen China	Patrol and track non-compliance mandates, and conduct thermal imaging for fever detection purposes.	(*204*)
Sanbot Elf	Out-of-hospital care, quality of life, continuity of work and education	Omnitech, Padova, Italy	Voice/face recognition, autonomous navigation and interact with patients	(*205*)
Moxi	Out-of-hospital care, quality of life, continuity of work and education	Diligent Robotics *Inc.*, Austin, TX, USA	Incorporated machine learning for perceiving and manipulating objects	(*206*)

Topic 2: Public Perception

1. Assessment of public web search

The quest for robotics technologies for infectious diseases has been widely covered by social media, web platforms, and news agencies during COVID-19 pandemic. In this regard, a systematic analysis of global user queries in public web searches correlated to the pandemic evolution may indicate trends and summarise some of the key requirements and unmet demands.

To this end, quantitative data was acquired from the Google Trends platform (Google LLC, California, USA) in a systematic keyword assessment within the period of November 2019 (01/11/2019) to January 2021 (latest access 15/01/2021) corresponding to the first global appearance of COVID-19 to gauge the public's interest. The first search has used the web-based API and considered the *worldwide* user interest in general pandemic search terms *covid-19*, *covid19*, *corona*, and *coronavirus* without restrictions on search categories or optional data filters. The case sensitivity of search terms was deactivated. For comparative reasons, the keywords *robot* and *robotics* were included for the same period. The obtained raw data (user interest ranking) was postprocessed using the Python Pandas framework and was clustered according to the median of monthly data.

Fig. S1 illustrates the results of user interests for the related search terms from Google web search during the first phase of the COVID-19 pandemic. The data set was normalized to the overall peak of global interest for keyword queries within the regarded period. This enables a quantitative comparison of web search queries for specific keywords. The interests depicted in Fig. S1 generally correspond to the course of the worldwide COVID-19 pandemic spread. More in detail, the web search interest increased after early cases in China were reported by media platforms in January 2020. User interests further grew when the first cases were reported in Europe, *i.e.* Italy, France, and Germany. The global peak occurred in March 2020 (> 50 % interest), when national lockdowns were imposed across Europe. Afterwards, the global attention decreased exponentially. Remarkably, the keyword *coronavirus* was twice as popular as *corona*. Keywords based on scientific terminology *covid-19* or *covid19* achieved less than 5% overall interest. This may indicate that the public perception of the pandemic is generally supported by colloquial terminology. For comparative reasons, public interest in generic keywords *robot* and *robotics* among specific pandemic terms was not significant (< 1% interest). Those findings on public perception and interests may be mapped to dissemination strategies of governmental campaigns and global media agencies in the early pandemic period. Users have employed the web search to explore auxiliary or different sources of information related to the COVID-19 virus. As demonstrated by Google Trend data, users adapted in the early phase a colloquial terminology for additional searches. This may be affected by strategies of the general media. Following the peak, the global interest decreased exponentially due to permanent news dissemination, individual saturation effects, and campaigns that were additionally launched to raise the COVID-19 awareness in the general public. The high global interest related to the first COVID-19 wave in March 2020 has not been replicated by the presence of the secondary wave in the Western hemisphere which started in late autumn. This may confirm that the permanent media coverage of COVID-19 has affected the long-term web search interest.

The second Google Trends analysis focused on dedicated robotic search terms with two sets of keywords for the given period. Following the results of the initial search, the first set consisted of composed colloquial keywords *robot corona* and *robot coronavirus*. Both terms were logically linked by Boolean operator AND and case sensitivity was deactivated. By analogy, the second set of composed keywords has been selected from terminology corresponding to reported robotic COVID-19 applications (see Section CURRENT STATE OF ROBOTIC SYSTEMS in the paper). The search terms included the following examples: *robot disinfection*, *robot delivery*, *robot nursing*, *robot surveillance*, *robot telepresence*, and *robot surgery*. Among those technology related search terms in Fig. S2, the term *robot coronavirus* has gained the highest interest within the considered period (> 50% global interest). This confirms the results of the previous search on general COVID-19 keywords. However, the peak of interest is shifted by one month to April 2020. This may be correlated to latencies in public dissemination, news reports, and social media contributions on novel technologies to battle COVID-19. In contrast, the public interest in *robot delivery* did not significantly alter after the first and during the second wave of COVID-19. This is constituted by a consistent interest rate of 10% within the regarded period. Besides, specific terms related to robotic technologies, such as *robot nursing*, *robot disinfection*, *robot surveillance, and robot telepresence*, that were occasionally disseminated to the general public (see the subsequent section on social media), resulting in less than 5% user interest. However, the latest data related to the second wave may indicate a slightly growing web search interest particularly in *robotic surgery* in autumn 2020 in combination with a general interest in robotic technologies for COVID-19 deployment. This trend may be driven within different communities by fear, firm predictions, and growing demands for technologies to handle the recurrent pandemic threat, i.e. second and third COVID-19 waves. To confirm this assumption, future data trends related to novel technologies must be monitored closely. Nevertheless, in comparison to the peak interests corresponding to the first COVID-19 wave, the latest data still reflects a limited interest in robotic technologies.

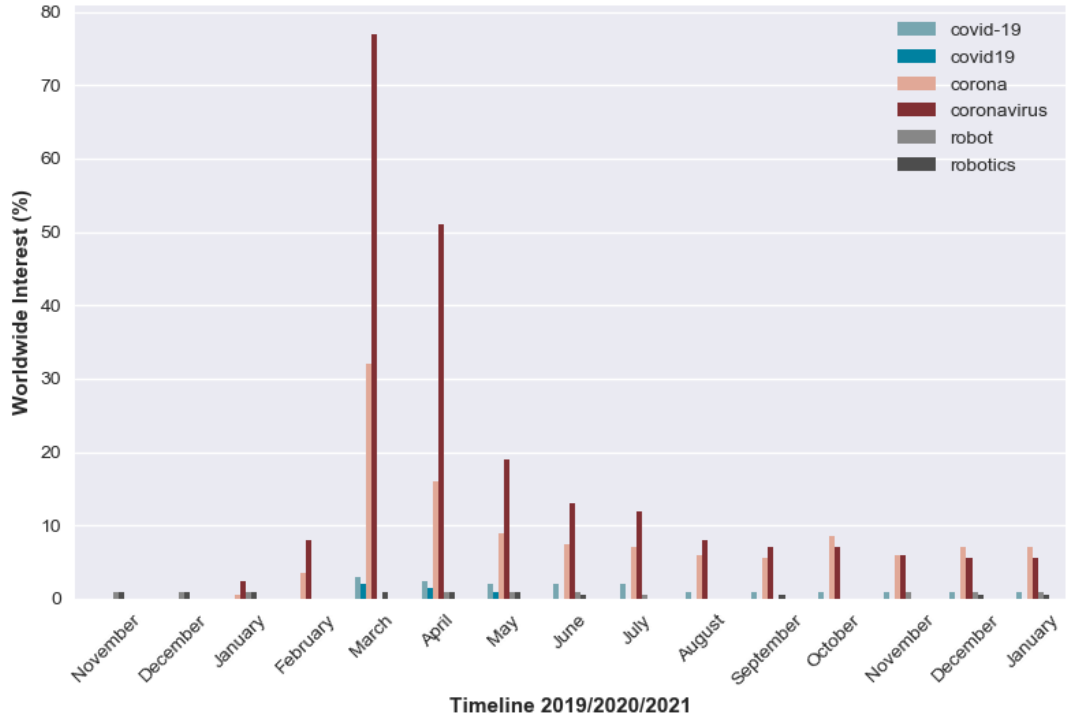

Fig. S1. Worldwide user interest for general web search terms during the COVID-19 pandemic. Data was acquired from the Google Trends platform. The interest ranking is normalized to the peak result within the regarded period. Scientific terminology (light blue, blue), colloquial terminology (peach, red), and comparative robotic terms (light gray, gray).

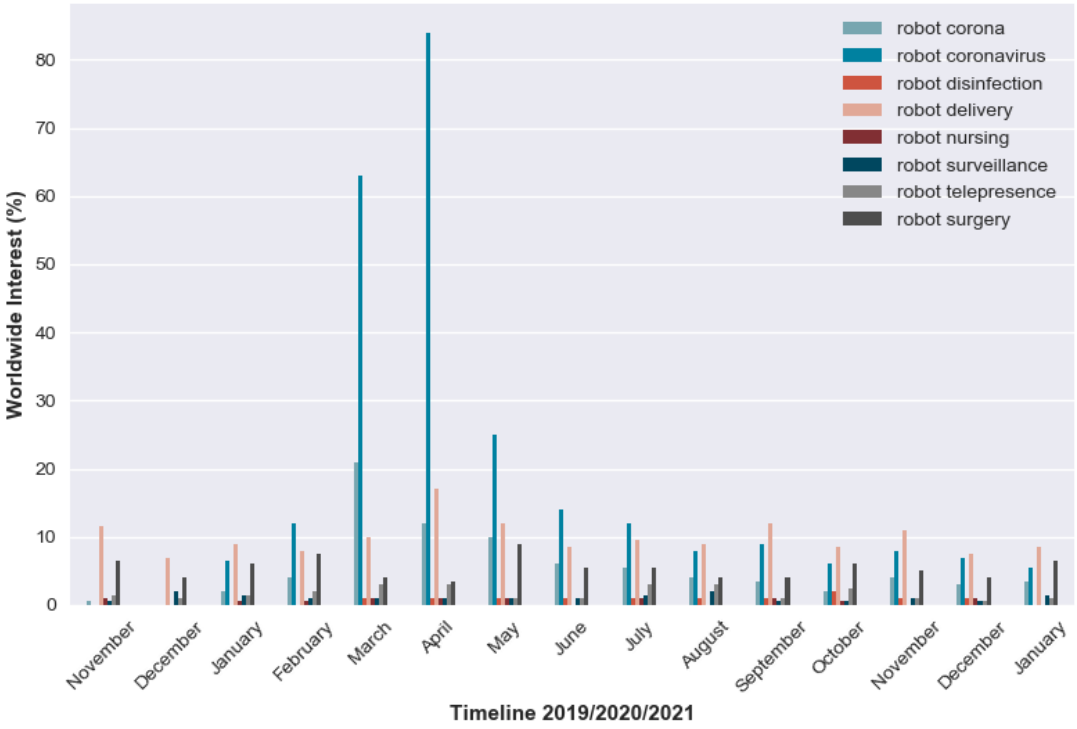

Fig. S2. Worldwide user interest in robotic technologies during the COVID-19 pandemic. Data was acquired from the Google Trends platform. The interest ranking is normalized to the peak results within the regarded temporal period. General composed terms (light blue, blue) and application-specific terms (orange, peach, red, navy, light gray, gray).

2. Examples of public perception in social media

Social media and news platforms can be utilized as an alternative instrument to the previous web search to analyze the public awareness and dissemination of robotic innovation throughout the COVID-19 pandemic. Information on recent events and technologies to combat COVID-19 was shared throughout the most common social media channels. Major platforms such as Facebook (2.5 billion users) (Facebook, *Inc.*, Menlo Park, CA, USA), YouTube (2 billion users) (YouTube, *Inc.*, California, USA), Instagram (1 billion users) (Facebook, *Inc.*, California, USA), Reddit (430 million users) (Reddit, Inc., Massachusetts, USA), and Twitter (386 million users) (Twitter, *Inc.*, California, USA) have supported the circulation of information.

In order to understand the elementary role of robotics in the COVID-19 pandemic and the awareness of robotic applications, such as listed in Section CURRENT STATE OF ROBOTIC SYSTEMS, in the general public, a set of social media platforms was systematically reviewed. Facebook has been excluded from the search. Review methodologies and results of the qualitative analysis are presented in the following paragraphs.

YouTube enables individuals to present content complemented by comprehensive video attachments. A systematic search was conducted using the advanced interface and subsequent keywords including Boolean operators: "*covid-19 AND robot" OR "coronavirus AND robot"*. The standard search language was English and results in the period of January 2020 to January 2021 were considered. In total, approximately 39k related media files were uploaded in the specified period (last access 15/01/2021). In order to identify relevant content, the results were ranked by view counts. This approach may reveal trends of popular contents within the user audience. The most relevant content (total view counts 100k to 550k) has been released by Chinese and Singapore news agencies (New China TV, CNA, South China Morning Post) on public safety including disinfection, reconnaissance, and temperature monitoring in the period of March to June 2020. Similarly, video articles disseminated by the most popular Indian educational channel (Study-IQ Education) on robotic applications in Indian hospitals and the podcast Great Big Story have addressed telepresence, social assistive, and delivery robots for fighting COVID-19 in India and recorded more than 230k views. Despite high view counts, the contents have only been commented by less than 2k users.

Within the range of 50k to 100k view counts, British and US news agencies, *e.g.*, The Telegraph, Guardian News or CNBC, and Al Jazeera English have disseminated predominantly robotic technologies for assistance and reconnaissance. Complementary to mass media, educational facilities (MIT CSAIL, NTU Singapore or University of Southern Denmark) have raised public awareness with specific contributions on in-house technology innovations, *e.g.*, warehouse disinfection, public surveillance, or automation of swab testing. In autumn, the official MIT channel has released one of the latest videos on robotic vital sign measurements (47k view counts). However, those view counts are lower in comparison to news agencies.

Video articles with less than 5k views commonly address key opinions or descriptions of specific technologies reported by mass media. In this regard, contents are summarized and presented by individuals. A remarkable fact is that views have peaked already in mid-March to April 2020. This correlates with previous findings from the Google web search. Furthermore, the number of channel subscribers especially for news agencies may reflect the findings. Nonetheless, user interaction, *e.g.* comments, was limited. This may indicate that **YouTube** is predominantly considered as a source of information with low user interaction.

Twitter (Twitter *Inc.*, California, USA) has its top three daily user activities located in the USA (64.2 million), Japan (48.5 million), and Russia (23.6 million) (Digital 2019 Global Digital Overview, DataReportal). Using a search interface based on the python module *TwitterSearch* (Carl von Linde-Akademie, TU Munich, Germany), results for twitter hashtags "*#covid19* AND *#robot" OR* "*#coronavirus* AND *#coronavirus"* were acquired (latest data acquisition 15/01/2021). Data covered the period of January 2020 to January 2021. The standard search language was English. Applying those constraints to the search results, the most relevant tweets (N = 200) were assessed regarding content, source, and specific user interests. Relevant Twitter channels listed in the following have more than 10k followers.

Four major sources of content were identified. Content was retweeted, linked by users to external (tech) news platforms (*e.g.*, @techreview, @cheddar, @thefuturisthq, @globaltimesnews, @businessinsider, @DigitalTrends, @Reuters), specifically created by companies/institutions (private/governmental), or was presented by tech-driven individuals and futurists with broad audience (*e.g.*, @BernardMarr > 130k followers, @SpirosMargaris, > 100k followers, @jblefevre60 > 75k followers, @Nicochan33 > 70k followers, @Paula_Piccard, > 50k followers). Most tweets (> 75%) were supplemented by media (video or images). Tweets have commonly described, commented on, and summarized recent emerging industrial/academic technologies or have outlined personal key options.

Throughout the first peak of the pandemic spread in the Western hemisphere (March – June 2020), technologies for robotic disinfections tasks in hospital (*e.g.*, @BlueOceanRobot, @ChinaDaily), public locations (*e.g.*, @FetchRobotics, @utm_my), warehouses (*e.g.*, @ZoneStrikeUVC, @UBTECHRobotics, @AvaRobotics, @MIT_CSAIL), and even airplanes (@CleanPlanes) were mainly presented. This has been complemented by tweets addressing delivery robots (@RefractionAI, @amazon) for people affected by COVID-19 quarantine.

Alternatively, strategies for improvement of public safety, such as in human-to-human contacts in food preparation and restaurant services, or nursing (*e.g.*, @cheddar, @businessinsider, @wef, @IndiaToday) were presented. Additionally, follower awareness was raised by the presentation of public engagement on low-cost platforms launched by educational institutes for sanitizing hospitals or care facilities (*e.g.*, @MSUmalaysia, @wef). Those strategies were accompanied by public dissemination of customized robotic designs or solutions, *e.g.*, by engineering students. Taking the experiences from the first COVID-19 wave into account, robotic and AI-driven technologies to fight loneliness in the elderly due to isolation or quarantine were frequently presented (*e.g.*, @Reuters). Novel robotic technologies for responding to COVID-19 effects were also presented in detail by the consumer technology association (@CTA) and in a focused Twitter coverage of the most influential tech event, *i.e.*, the CES annual trade show in January 2021 (@CES).

Besides technologies, high follower numbers of fintech influencers were also used to discuss socio-economic and socio-cultural pandemic impacts of robotic deployment to the job market (@efipm, ~ 10k followers). Lastly, social support to thank healthcare workers was realized in urban and densely populated areas with aerial drone patterns (@UVify). Robotics for fighting COVID-19 has been disseminated via twitter channels with low (< 1k) to high follower rates (> 100k). Qualitative assessment of twitter metrics in terms of replies, likes, and retweets has generally shown limited user interaction. On average, only few users (< 50) have interacted, replied, or retweeted the posts. Analysis of account biographies has shown that those were frequently from tech, educational or academic backgrounds. However, the number of tweets did not significantly alter after the first or within the second COVID-19 wave. Those search results corroborate the previous web search interest and confirms the limited awareness to **Twitter** communities of AI and robotics enthusiasts.

This work further analyzed the circulation on photo and video network **Instagram**. Based on previous keywords, a limited number of results for posts of associated hashtags was identified using the python module *python-instagram*: #covid19robotics (1 post), #covid19robot (39 posts), #covid19robots (13 posts), #coronarobots (15 posts), #coronarobot (103 posts), #coronavirusrobot (42 posts) (latest access 15/01/2021). Companies, governmental institutions, and individuals are the most common platform users. For example, existing robotic technologies applied to COVID-19 challenges have been generally illustrated and support by media publications (*e.g.*, @ubtechrobotics), presented socially assistive robots (@reliablerobotics), or targeted disinfection strategies (@fellag_uvc.robot, @speedycare_kuwait). Remarkably, robotic strategies to control COVID-19 in developing countries were disseminated via **Instagram** by *e.g.*, Nigerian news aggregation and tech startups (@covid19worldupdate, @naijastartups), Sudanese inventors (@mohamedbaloola), or involved educational facilities in Nigeria (@bredhub). Beyond that, several artists were inspired to create and publish pandemic robotic art (@robottoday, @corona_comic). Relevant content on **Instagram** was contributed by individuals, SMEs, or startups. Interestingly, African users have dominated tech-related posts. This may demonstrate the different target audiences of the platform and is, *e.g.*, in the Western hemisphere very likely focused on lifestyle, brands, and advertisement. Nevertheless, the relevance of robotic technologies for COVID-19 on **Instagram** is still limited due to low numbers of related user posts.

Lastly, the **Reddit** platform combines social news aggregation, web content listing, and discussion panels and has shown increased popularity in Anglo-American countries. A systematic search was conducted using the advanced Reddit search interface using English keywords: *covid19*, *robotics*, *robot*, *coronavirus* (last access 15/01/2021). In contrast to previous platforms, discussion and circulation of relevant information have been very limited for the considered period from January 2020 to January 2021. Very few posts (< 60) were identified that generally reposted content linked to released **YouTube** or **Twitter** posts, *e.g.*, disinfection robots or prototypes from academic competitions.